



Province of British Columbia
Ministry of Energy, Mines
and Petroleum Resources
Hon. Anne Edwards, Minister

ORE DEPOSITS, TECTONICS AND METALLOGENY IN THE CANADIAN CORDILLERA

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Canadian Cataloguing in Publication Data

Main entry under title:

Ore deposits, tectonics and metallogeny in the
Canadian Cordillera

(Paper, ISSN 0226-9430 ; 1991-4)

Includes bibliographical references: p.
ISBN 0-7718-9150-4

1. Mines and mineral resources — Rocky Mountains,
Canadian (B.C. and Alta.) 2. Metallogeny — Rocky
Mountains, Canadian (B.C. and Alta.) 3. Geology,
Structural — Rocky Mountains, Canadian (B.C. and
Alta.) I. McMillan, W. J. (William John) II.
British Columbia. Ministry of Energy, Mines and
Petroleum Resources. III. Series: Paper (British
Columbia. Ministry of Energy, Mines and Petroleum
Resources) ; 1991-4.

TN26.073 1991

553'.09711

C92-092044-6

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TECTONIC EVOLUTION AND SETTING OF MINERAL DEPOSITS IN THE CANADIAN CORDILLERA

by William J. McMillan

PREFACE

Like the scenery of 'supernatural' British Columbia, mineral deposits of the Canadian Cordillera are diverse and exciting. What we attempt to do in this publication is to put the various classes of deposits into their tectonic, stratigraphic and chronological settings. We use examples, but our focus is toward the broader scene: where do the deposits occur, what are their characteristics, when did they form, where should we look for others, what should be here that we haven't found yet? We use specific Cordilleran examples to explain the derivation of the models we describe but, since neither mineral deposits nor geology respect political boundaries, the models are applicable on a world scale, and, of course, many are based on deposits found elsewhere in the world.

We don't have every possible type of deposit in the Cordillera, but the same forces that caused our supernatural scenery, also richly endowed the Cordillera with mineral resources.

This report progresses from the general to the specific. The first paper provides a tectonic overview and sets the mineral deposits into this framework. The following two papers discuss deposits in North American rocks, and subsequent presentations focus on mineral deposit types in accreted and 'suspect' terranes; deposits formed at or near the sea floor or from hot springs; and those formed in successively deeper zones as magmatic deposits, vein to replacement deposits, skarns, and porphyries. Many of the deposits in accreted, island-arc rocks are related to convergent, often destructive, plate margins or collisional boundaries. Assembly of the Cordillera, as we know it, was largely completed by Early Tertiary time but mineralizing events did not stop with assembly so we devote some attention to post-accretionary deposits.

From a different perspective, the papers examine deposits within and directly linked to intrusive rocks (magmatic, porphyries, skarns), replacement

deposits, possible manto deposits, deep to shallow veins and related deposits formed at the surface, volcanogenic massive sulphides and sedex deposits. But, we try to view these deposit types in a broader regional tectonic or plate tectonic context.

No attempt is made in this report to cover sedimentary-hosted deposits of gypsum, barite, phosphate and other industrial minerals. Nor are coal, uranium, pegmatite-hosted deposits, molybdenum porphyries or some of the less common deposit types such as carbonatites, tin greisens and placers discussed.

ACKNOWLEDGMENTS

Obviously those who presented the workshop that formed the basis of this report did not "do it alone". We wish to acknowledge those who helped us. Shaun Pattenden, Mike Fournier, and Bob Paul coordinated logistics, drafting, slide preparation, production of the Workshop Manual, and generally shepherded the course to completion on schedule. Thanks are extended to Kathryn Andrew (Dunne) for background and other work on the "Volcanogenic Massive Sulphide" presentation; Ian Webster for work on the "Skarns" report; Pat Desjardins for his efforts on the "Sedex Deposits" paper; Jan Hammack for background and other work on the "Mineral Deposits in Mafic Rocks" contribution; Bob Gaba for volunteering to help with logistics during the Workshop; and Dick Player for photography. We also thank the Editors, Brian Grant and John Newell, and our draftsmen, John Armitage, Pierino Chicorelli, and Martin Taylor, for their efforts. Without the help provided by these, and other people, the Workshops and this report would never have materialized.

Individual chapters were improved by comments from external reviewers, who are acknowledged in each chapter; to them we extend our thanks.

INTRODUCTION: TOWARDS A METALLOGENY

by Andrejs Panteleyev

The first comprehensive description of Cordilleran metallogeny was by A. Sutherland Brown, R.J. Cathro, A. Panteleyev and C.S. Ney in 1971. That discussion of mineral deposits was within a basic eugeosyncline-miogeoclinal framework, without elaboration about the then-new, evolving theories of plate tectonics. Since then there have been a number of significant updates of the subject, all within a plate tectonic context. These include: Wolfhard and Ney, 1976; Sinclair, Wynne-Edwards and Sutherland Brown, 1978; Tempelman-Kluit, 1981 and McMillan, Panteleyev and Höy, 1987.

The Canadian Cordillera currently (1992) has documentation for more than 10 550 mineral deposits and occurrences in the British Columbia mineral inventory file (MINFILE); 1367 deposits are listed for the Yukon Territory in the (1987) CAN-MININDEX file.

The most recent and comprehensive work to date is the chapter on metallogeny (Chapter 19) in the much-awaited volume *A Decade of North American Geology (DNAG)*; The Cordilleran Orogen: Canada; edited H. Gabrielse and C.J. Yorath, 1991. The following thoughts are from the introductory section of Chapter 19 of the DNAG volume, Regional Metallogeny, by K.M. Dawson, A. Panteleyev, A. Sutherland Brown and G.J. Woodsworth:

"The Canadian Cordillera is a region of great geologic and metallogenic diversity. Just as each Cordilleran terrane preserves a stratigraphic record different from that of neighbouring terranes, characteristic suites of mineral deposits, as integral parts of their host terranes, reflect fundamental differences in their depositional environments. The miogeocline and displaced equivalents in the eastern Cordillera, as well as each of the terranes comprising the accreted collage of the western Cordillera, pose unique lithotectonic characteristics that are reflected in the types of mineral deposits they contain.

"Predominantly stratiform deposits of Zn, Pb, Cu, Ba and Fe, and skarn deposits of W, Zn, Pb, Mo, and Sn are hosted by layered sedimentary strata of the ancestral North American miogeocline. The similar types of mineral deposits of displaced (Cassiar) and/or deformed (Kootenay, Nisling) continental margin terranes support their cratonic linkage.

"Stikinia and Quesnellia, which together constitute the bulk of the Intermontane Superterrane, host a suite of mineral deposits typical of their predominantly calcalkalic volcanic-arc composition: abundant porphyry Cu, Mo deposits, Cu, Zn volcanogenic massive sulphides, Cu and Au skarns, and Au, Ag veins. On the other hand, the ophiolitic Cache Creek and Slide Mountain terranes of the

Intermontane Superterrane display distinctive kinds of mineral deposits typical of their oceanic origin: magmatic Cu, Ni, volcanogenic Cu, Zn and mesothermal Au veins, in addition to ultramafic pluton-related asbestos, jade, Cr and PGE (platinum group elements) deposits.

"The dominantly arc volcanic character of the diverse terranes of the Coast Belt is reflected in their metallogeny: volcanogenic Cu, Zn, porphyry Cu, Mo, mesothermal Au, and epithermal (sic) Au, Ag, Sb, Hg veins. The lithologies of both Wrangellia and Alexander Terrane of the Insular Superterrane represent several depositional settings and host commensurate suites of mineral deposits including platformal sediments with stratiform gypsum and barite, oceanic arc volcanics with volcanogenic Zn, Cu, Ag, Pb, Ba; porphyry Cu, Mo and Au veins; ocean rift volcanics with volcanogenic Cu, Co, Ag, Mn, and magmatic Ni, Cu, PGE; and carbonate strata hosting Fe, Cu, and Au skarns.

"In addition to the fundamental relationship between terrane crustal types and differences in origin, type, and distribution of contained mineral deposits, mineral deposits can be classified further in relation to the time of terrane accretion as pre-accretionary, accretionary and post-accretionary. Deposits formed prior to the amalgamation of the

TABLE 1-1

Metallogenesis — Recent Advances

- I. Tectonic interpretations (lithotectonic framework)
 - Accretionary tectonics
 - Continental margin evolution

II. Mineralization process interpretations

Direct Observations

- Ocean ridge hydrothermal vents (black smokers)
- Hotsprings, geothermal resources

Models (empirical → genetic)

- Fluid inclusions
- Radiometric dating
- Isotope studies
- Geochemistry
 - phase relations
 - minor elements
 - aqueous solutions
- Magmatic processes and hydrothermal fluid evolution
- Computation of processes
- Low-temperature hydrothermal phenomena, weathering and supergene processes

host terrane with others, and prior to subsequent accretion to the North American craton may have undergone significant modification and redistribution due to accretionary metamorphic, plutonic, and hydrothermal processes. Comparison with examples in the western United States, Mexico, and Australia demonstrates that not only are certain syngenetic pre-accretionary deposits uniquely associated with specific types of terranes, e.g., manganiferous chert in oceanic terranes, and Kuroko-type volcanogenic massive sulphides in calcalkaline island arcs, but also accretionary and post-accretionary deposits regardless of age, correlate strongly with host and/or basement lithology."

The accompanying table (Table 1-1), is a graphic summation of major areas of geologic study that have led to recent advances in our knowledge of Cordilleran metallogeny. Notwithstanding the superb progress that has been made, large gaps still exist in our understanding of Cordilleran metallogeny.

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OVERVIEW OF THE TECTONIC EVOLUTION AND SETTING OF MINERAL DEPOSITS IN THE CANADIAN CORDILLERA

by William J. McMillan

INTRODUCTION

The Canadian Cordillera contains a wealth of mineral deposits that invoke both exploration and research interest. This introduction will explore several themes in attempting to understand the distribution patterns of deposits in this geologically and structurally complex area. First, metallogeny is a large-scale feature that is intimately linked with plate tectonism; second, metallogenic epochs are characteristically times of widespread igneous activity — plutonism or volcanism; and third, although it cannot be used to predict the location of individual deposits, plate tectonic activity localizes mineral districts. In accordance with these themes, the following material reviews selected tectonic and metallogenic concepts.

DEFINITIONS AND CONCEPTS

It is important to describe the terms that are used in this review. There are three end member types of plate tectonic boundaries; divergent, convergent and transcurrent (Figure 2-1). **Divergent** boundaries exist along the east coast of North America, as the Atlantic Ocean opens and the North American plate moves "passively" westward. Historically, rifting events that reflect periodic divergent motion occurred from Proterozoic through to early Mississippian time along the former western edge of the Cordillera, in what are now the Rocky Mountains. The Marianas, Taiwan, Andean, and Himalayan types are modern examples of **convergent** plate boundaries (Figure 2-1). The **Marianas**-type, which involves only oceanic crust, represents the initial stages of closing of an ocean basin. As closure continues, continental crust becomes involved. At a **Taiwan**-type boundary, continental crust impinges on oceanic crust, whereas at an **Andean**-type, oceanic crust impinges on continental crust. When an ocean basin closes completely, continental slabs collide. The **Himalayan** boundary records such a collision and similar tectonism results when island arcs are welded to continents. **Transcurrent** boundaries, like the San Andreas–Queen Charlotte fault system, may also occur. Some terminology for wrench or strike-slip faults may be useful. Movements between adjacent, en echelon, strike-slip faults create either compression or extension in the connector zones (Figure 2-2). Thus the connector zone may be characterized either by transpression with uplift and

thrusting or by transtension with formation of extensional basins, perhaps accompanied by magmatism and volcanism. Large offsets that occur require decoupling of the fault block, probably at mid-crustal or shallower depths (Bally and Oldow, 1986). The Cordillera has been an active margin, particularly since 185 million years ago, with the North American plate moving westward across the subduction zone (Monger, 1991). Thus the motley collage of pre-accretionary and accretionary rocks that now make up the Cordillera record a history of divergent, convergent, oblique and transcurrent movements.

Density variations cause colliding edges to be **subducted**, that is pushed under an adjacent plate, or **obducted**, to override the adjacent plate. The angle of subduction appears to be partly a function of relative plate velocity. It can vary along the axis of a volcanic arc and markedly influences the width of the arc formed, its structural development, and the composition of the magmas produced (Figure 2-3). The type of magma generated varies both across and along arcs; complicated changes can also result as centres of igneous activity shift and encounter different kinds of mantle material.

Suture zones are collisional plate boundaries where adjacent plates have become welded together. Underplating occurs where slabs of subducting crust become sutured to the overriding plate. LITHO-PROBE deep seismic studies across Vancouver Island (Clowes *et al.*, 1987) indicate that Devonian to Jurassic rocks of Wrangellia form an enormous thrust sheet 400 by 100 kilometres in size and 10 kilometres thick. It is underplated by downward-younging, fault-bounded, Cretaceous, Tertiary and Recent material accreted during late Mesozoic to Recent, Pacific Ocean floor subduction. Interpretative crustal cross-sections suggest that much of the Cordilleran crust may have originated in a similar way (Monger, 1989, Vasek *et al.*, 1989 in press).

Where adjacent plates diverge, they produce **extension** or **rifting** that is often accompanied by volcanism along the spreading axes or ridges, like the mid-Atlantic ridge, or Middle Valley off the British Columbia coast, which mark pull-apart zones. If the plates meet obliquely, movement is partly transcurrent and they slide past each other along the contact. Bally and Oldow (1986) describe differing related igneous activity and deformation for each of the collisional boundary types.

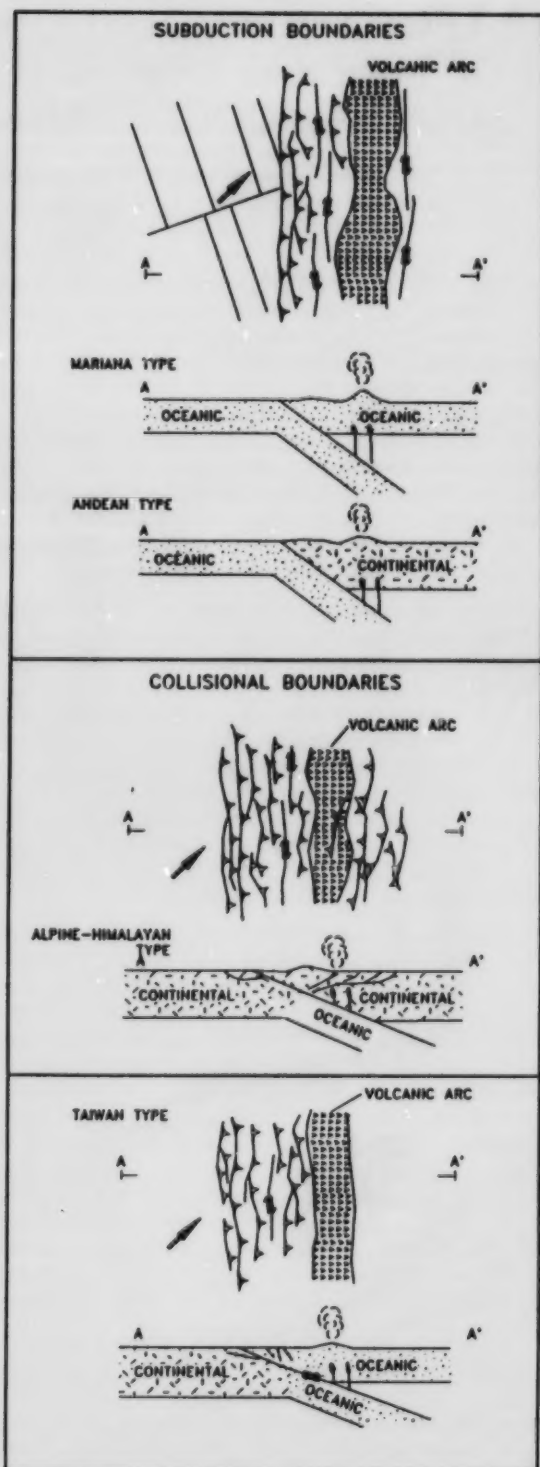


Figure 2-1. Typical collisional boundaries between tectonic plates illustrating the influence of the types of crust and mantle involved (after Bally and Oldow, 1986).

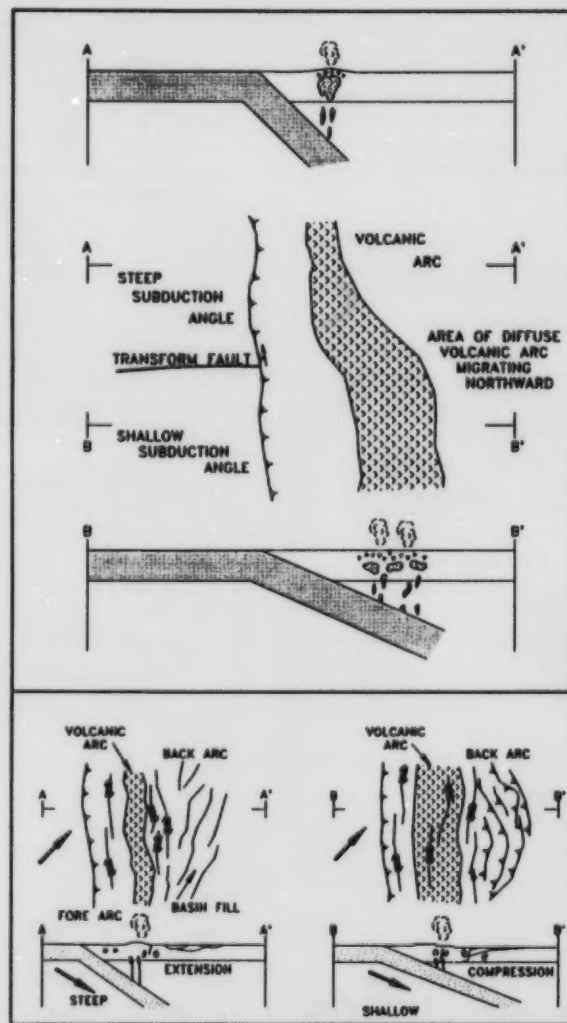


Figure 2-2. The relative steepness of the angle of subduction influences both the width and character of the volcanic arc. It also affects the tectonic regime; steeply subducting slabs commonly cause extension and basins develop behind the volcanic arc, whereas shallow angles generally cause compression and backarc fold and thrust belts develop (after Bally and Oldow, 1986).

Various terms are used to describe stratigraphic packages identified during tectonic and stratigraphic mapping in the Cordillera. Terranes are defined as crustal slabs with distinctive internal stratigraphy that are generally in faulted contact with adjacent slabs. These contacts may be steeply to gently inclined. Each is characterized by a geological history that is distinct from contiguous terranes (Monger, 1989). Terranes can be produced by plate tectonic movements or by fault offsets.

The Canadian Cordillera is made up of rocks of North American parentage, those that originated elsewhere (although they are not necessarily far-travelled), and suspect terranes, those of uncertain parentage. Some suspect terranes are fault-displaced parts of the ancient continental margin, some are pericratonic and probably originated off the edge of the North American plate, although perhaps far south of their present positions. Numerous terms have been coined to describe aspects of the interactions between terranes. **Amalgamation** describes the welding together of adjacent terranes. **Superterrane**s consist of several terranes that have amalgamated. **Accretion** refers to the joining or docking of travelled and suspect terranes with the North American plate. Establishing the timing of terrane linkages is based on overlap by stratigraphic units, recognition of debris from one eroded onto the other, and the stitching of mutual boundaries by intrusions. It is important to keep in mind that once accreted, a terrane becomes part of the North American plate, hence new continental basement.

THE CANADIAN CORDILLERA

The Canadian Cordillera consists of five major tectonostratigraphic belts that originated during Mesozoic to post-mid Tertiary events; east to west they are the Foreland, Omineca, Intermontane, Coast and Insular belts. The Cordillera is a collage of pericratonic and accreted terranes welded to the western edge of the North American craton. Since docking, large-scale strike-slip and other displacements at terrane boundaries have juxtaposed unrelated terranes, and units within terranes have been disaggregated by movements along internal major faults to produce the present configuration. As Monger (1989) notes: "extensional tectonics dominated the evolution of the western margin of the North American continent from Middle Proterozoic through Middle Jurassic time, and compressional tectonics thereafter", and post-Middle Jurassic relative movement is apparently immense. Engebretson (1983), using magnetic anomaly patterns and hot spot traces, calculated that more than 10 000 kilometres of Pacific Ocean crust have slid beneath the western margin of North America in the last 145 million years.

In *Geoscience Canada*, Gabrielse and Yorath (1989) present a summary of the history of development of the Cordillera that summarizes their report for the *Decade of North American Geology* volume. In another contribution to the volume, Dawson *et al.* (1991) describe the regional metallogeny of the Cordillera.

NORTH AMERICAN ROCKS

The Foreland Belt consists largely of material deposited in extensional settings and derived from cratonic sources. The rocks are divided into three stratigraphic packages based on lithology and age

relationships. Beginning in Middle Proterozoic time, episodes of rifting created a thick, passive margin sequence along the edge of the North American craton. The initial, 1200 Ma, event is evidenced by two thick, clastic and carbonate sequences, the Purcell (or Belt) Supergroup in the south, which hosts the famous Sullivan lead-zinc-silver massive sulphide deposit, and the Wernecke Supergroup in the north. Rifting the full length of the Cordillera led to deposition of the second sequence, the late Proterozoic (770 Ma), dominantly clastic Windermere Supergroup. Mafic dikes and flows of this age are widespread and volcanic-exhalative cherty iron formation occurs in the McKenzie Mountains. The third sequence, which is related to a mid-Devonian to Early Mississippian rifting event, led to formation of the "sedex" barite-lead-zinc massive sulphide deposits of the Kechika trough and the Selwyn basin (Figure 2-4). Rifting was accompanied by deformation, volcanism and plutonism at the craton margin (Nelson and MacIntyre, 1989). Platform carbonates of this age host Mississippi Valley-type lead-zinc deposits, like Robb Lake. Examples of significant mineral deposits along the ancient continental margin are listed in Table 2-1. Later, during Mesozoic and Cenozoic times, the miogeocline was affected by compression and magmatic activity during accretion of island-arc terranes, and cut by Cretaceous and Cenozoic dextral strike-slip faults.

ACCRETED ROCKS

Two Mesozoic metamorphic-granitic belts, the Omineca and Coast belts, run the length of the Canadian Cordillera. These are interpreted to be suture zones where the leading edges of two major composite accreted terranes — the Intermontane and Insular superterrane — crumpled into the North American plate (Figure 2-5). Although the conclusion is not universally accepted (see Price and Carmichael, 1986), Irving *et al.* (1980) and Tipper (1984) argue from paleomagnetic and paleontological data that individual elements of these superterrane originated far to the south of their present locations. Moreover, Monger *et al.* (1982) argue that as the terranes moved northward they amalgamated to form the distinct Superterrane — before they docked with North America (Figure 2-6).

The Intermontane Superterrane consists of the oceanic Slide Mountain and Cache Creek terranes, and the island-arc Quesnel and Stikine terranes. Stikinia, the Cache Creek Terrane and Quesnellia may have been linked (amalgamated) by latest Triassic time. Closing of the Slide Mountain ocean began in the late Paleozoic and apparently ended with mid-Jurassic to Early Cretaceous thrusting of the Slide Mountain and to a lesser extent Quesnellia allochthons onto the miogeocline. In the northern Cordillera, the Teslin suture zone, which formed during oblique Triassic-Jurassic convergence that resulted in dextral offset, now separates accreted and

North American rocks (Hansen *et al.*, 1989). Closure of this ocean basin may be in part responsible for formation of the Quesnellia island-arcs. The Intermontane Superterrane collided with the North American craton in mid-Jurassic time, about 185 to 175 Ma, giving rise to the Omineca crystalline belt.

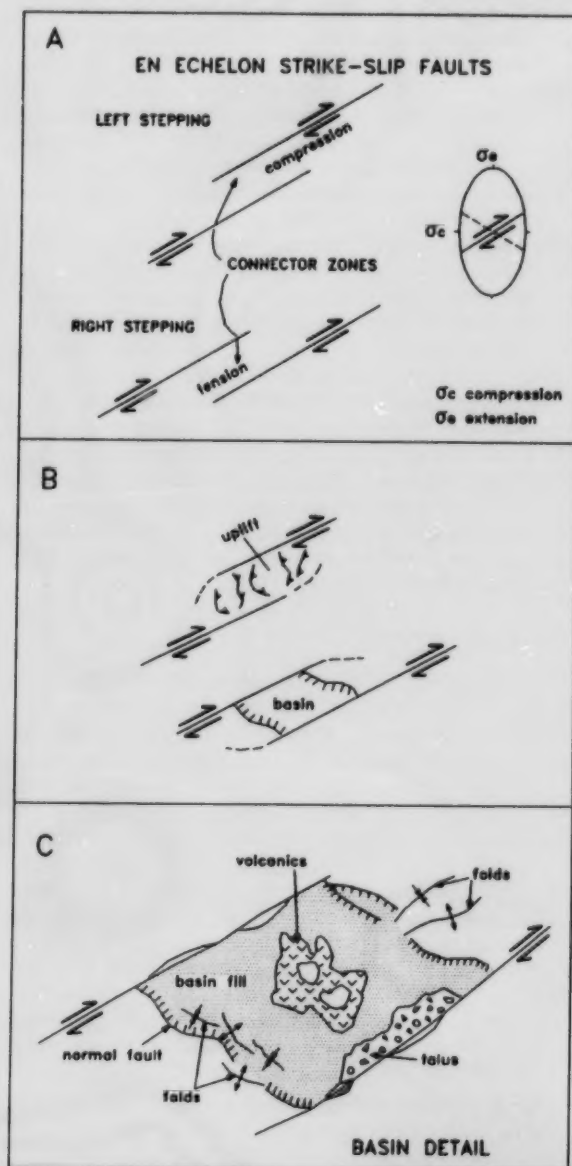


Figure 2-3. Typical en echelon strike-slip faults can cause compression or extension depending on whether they step left or right across their connector zones, therefore the connector zones may be transpressional resulting in uplift and developing compressional faults (A), or be transtensional and form extensional basins (B). In the extensional settings, deep seated fractures may tap magmas to feed volcanic activity at the surface (C) (after Bally and Oldow, 1986).

Debate continues. One school of thought is that the combined Intermontane and Insular superterranes were at their present relative positions by mid-Cretaceous time; another is that they were against North America but farther south, as "Baja B.C.", at that time and did not arrive at present latitudes until Early Tertiary time. A different hypothesis is that the Stikine 'block' originated in the Columbia embayment and began its travels northward in Middle to Late Jurassic time when the early-arriving, southern part of Wrangellia collided with continental North America (Wernicke and Klepacki, 1988). Obviously these various interpretations present age and geographic anomalies that require resolution.

The major internal elements of the Insular Superterrane — the Alexander Terrane and Wrangellia — were together by mid-Pennsylvanian time (Gardner *et al.*, 1988). In the middle Cretaceous, at about 100 Ma, the Insular Superterrane collided with the west side of the Intermontane Superterrane, initiating formation of the Coast plutonic-metamorphic belt.

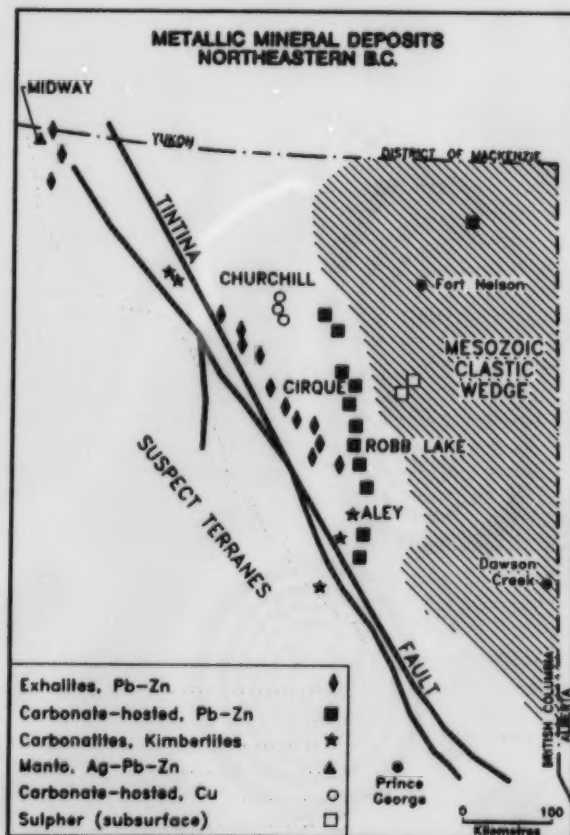


Figure 2-4. Mid-Paleozoic rifting was accompanied by emplacement of carbonatite magmas and formation of barite, lead-zinc exhalative (Sedex), carbonate-hosted lead-zinc and copper replacement deposits in miogeoclinal rocks of the Canadian Cordillera (after Nelson and Machty, 1989).

TABLE 2-1

Deposit Types and Potential, Including Most Significant Past Discoveries

Type	Com-modities	Best Known Example	Tonnage	Grade
Sedex	Pb, Zn, Ag, Ba	Cirque	40 million tonnes	2.2% Pb, 7.8% Zn 47 g/t Ag
Mississippi Valley type	Pb, Zn; Ga, Ge?, S	Robb Lake	5.5 million tonnes	7.3% Pb-Zn
Carbonatite Kimberlite	Nb, Ta, REE	Aley	significant	1-1.5% Nb ₂ O ₅
Manto	Ag, Pb, Zn	Midway	1.2 million tonnes	410 g/t Ag, 7% Pb, 9.6% Zn

Elements of the oceanic Bridge River Terrane range in age from Paleozoic to Early Jurassic. The Bridge River accretionary complex contains blueschist that is Late Triassic in age but imbrication of these and adjacent rocks was an Early or Middle Cretaceous event. Further, the Shulaps ophiolite complex apparently was thrust westward over rocks of the Bridge River Terrane during closing of the Bridge River-Cache Creek ocean basin, an event that began prior to Late Cretaceous time (Archibald *et al.*, 1990). Monger *et al.* (1982) argued that Bridge River Terrane docked against the Intermontane Superterrane, probably as an accretionary wedge, in earliest Cretaceous time, about 140 Ma.

Although it is not well constrained, strike-slip faulting probably began in the northeastern Cordillera in the Late Cretaceous. According to Price and Carmichael (1986) the Tintina-Northern Rocky Mountain trench is an intracontinental transform-fault system with about 450 kilometres of dextral offset (Figure 2-7). Late Cretaceous to Paleocene movement was transferred southeastward as oblique convergence in the southern Canadian Rockies, whereas mid-Eocene movement was transferred southwestward into the Fraser-Straight Creek fault system by means of shear and east-west crustal stretching in the connector zone. There is a problem; this interpretation does not allow the apparent 1300-kilometre offset and 45° clockwise rotation relative to the craton in post-Middle Cretaceous time predicted from paleomagnetic results (Symons and Wellings, 1989). This problem remains unresolved.

An interesting test of the timing and, to a lesser extent, geographic interpretations is to examine clastic wedges in the Foreland Belt (Figure 2-8). For example, Slide Mountain or Cache Creek debris that was shed into the Upper Jurassic Monteith Formation in the Foreland Belt resulted from docking of the Intermontane Superterrane, that began in Middle Jurassic time. Similarly, although stratigraphic ties are open to argument, Foreland sedimentary clastic wedges are interpreted to record effects of emplacement of the Bridge River, Cascades and other ter-

ranes. Accretion of the Insular Superterrane, beginning in the Early Cretaceous, is interpreted to have led to deposition of the Campanian (about 80 Ma) Belly River Formation (Cant and Stockmal, 1989; Gabrielse and Yorath, 1989). Obviously, sedimentary wedges that are byproducts of terrane accretion can lag accretion by several tens of millions of years.

In the Omineca Belt, metamorphic rocks record deep structural depression during mid-Jurassic tectonism, followed by significant uplift; by Late Cretaceous time the Omineca and Coast plutonic-metamorphic belts were well established and being uplifted (Gabrielse and Yorath, 1989). Metamorphic core-complexes in the Omineca Belt were further exhumed by mid-Cenozoic uplift and detachment faulting (Coney, 1989). By the Late Cretaceous,

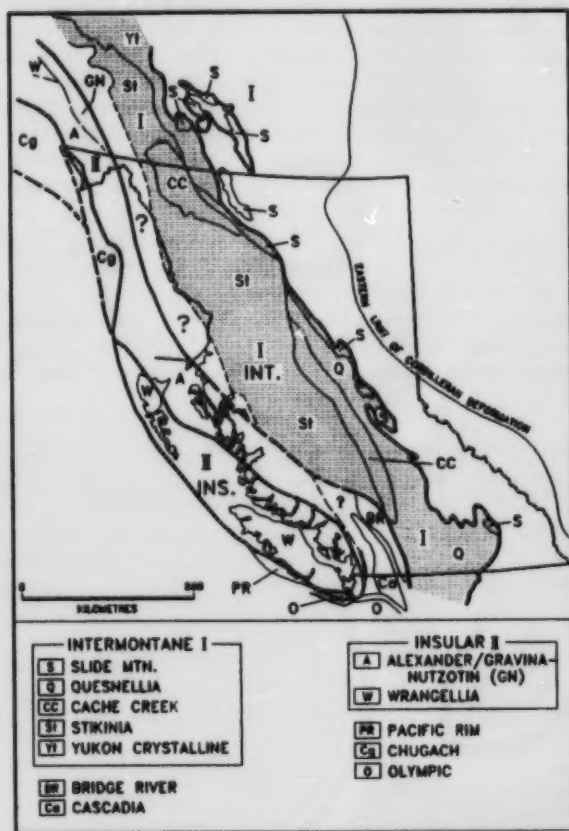


Figure 2-5. Major tectonic elements of the Canadian Cordillera showing terranes that comprise the Intermontane (Stikinia, Cache Creek, Quesnellia and Slide Mountain-Yukon Crystalline) and Insular (Wrangellia and Alexander-Gravina-Nutzotin) superterranes as well as several smaller terranes (Bridge River, Cascadia, Pacific Rim, Chugach and Olympic). The figure illustrates the large number of apparently accreted tectonic slices or terranes that compose the Canadian Cordillera (modified after Monger *et al.*, 1982).

Coast Range debris was shedding into Georgia Basin and compression shifted the belt eastward, narrowing the Tyaughton trough-Methow basin and perhaps initiating Shulaps overthrusting.

Along the eastern side of the Coast Range, the so-called "Coast megasequence" originated at about 70 Ma. An incredible 800 kilometres of the megasequence are occupied by a foliated tonalite body. It is not certain whether this body is intrusive or a deep crustal slab, analogous to the Kapuskasing High in eastern Canada (Percival and Card, 1983). The Juneau gold belt, which has produced more than 95 per cent of Alaska's lode gold, is associated with the megasequence (Gabrielse and Yorath, 1989).

During the Eocene widespread granitic magmatism and uplift occurred in the Coast and Omineca belts. The Omineca Belt also displays up to 100 kilometres of extension accompanied by volcanism and high heat-flow rates. Dextral strike-slip faulting continued and movement began on the Fraser-Yalakom system. Paleomagnetic studies show that the Eocene Kamloops volcanics (Symons and Wellings, 1989) and the mid-Eocene Ootsa Lake volcanics (Vandall and Palmer, 1990), have the same pole as the craton, so the Intermontane Superterrane was cratonized by mid-Eocene time.

At least some of the reason for this change from compression to extension and uplift lies in large scale shifts in plate movement vectors (Engebretson *et al.*, 1985). About 150 million years ago, relative movement between the Pacific and North American plates was easterly. By 100 Ma it shifted to northeast

and by 50 Ma to east-northeast (Figure 2-9). Near the continental edge, at about 85 Ma, the Kula plate broke off from the Pacific plate and moved north relative to North America. About 40 Ma the Kula plate amalgamated with the Pacific plate, when a new Farallon-Pacific-North American plate triple-junction originated off the north end of what is now Vancouver Island. Today, motion north of the triple junction continues to be northward relative to the North American plate (Gabrielse and Yorath, 1989).

In Neogene time, Pacific-Juan de Fuca-North American plate interactions have been key. The spectacular Cascades volcanoes are one of the results.

SUMMARY

In general, from Jurassic through Eocene time, episodes of deformation, plutonism and volcanism within the Cordillera correlate well with changes in velocity or movement direction of the North American Plate relative to oceanic plates. Relative collision vectors were often oblique to terrane boundaries during amalgamation and docking events. Consequently, timing of collision and related plutonic events varies along the length of the Cordillera. The curved to uneven shapes of the leading edges of rafting island-arcs and the North American plate border would be a major influence on variations in local stress regimes; the same movement vector could generate local compressional, extensional or transverse forces. These forces provide ground prep-

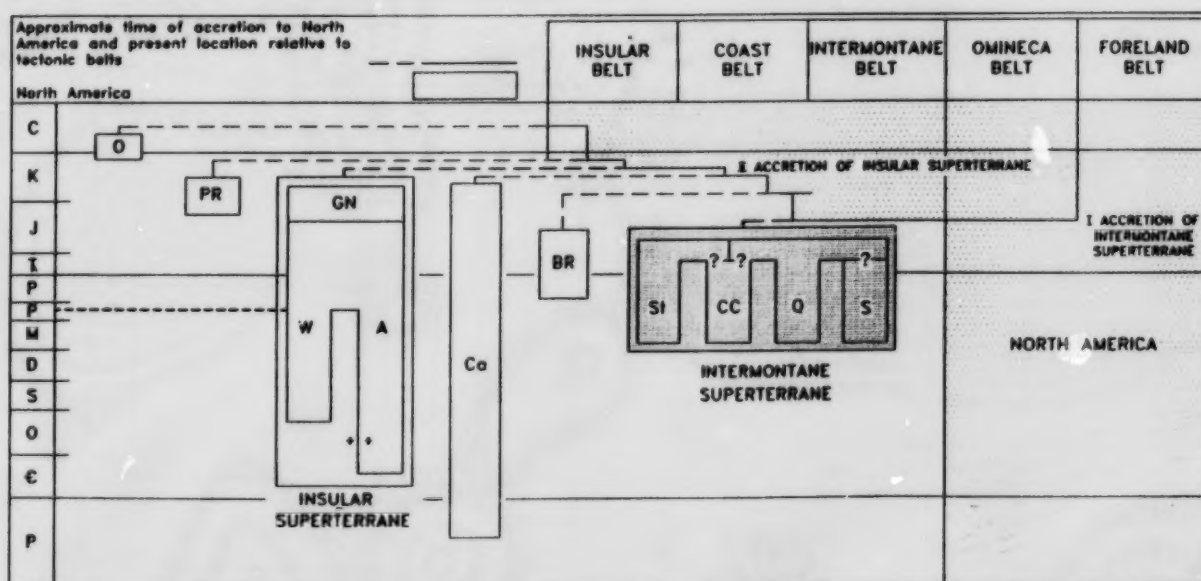
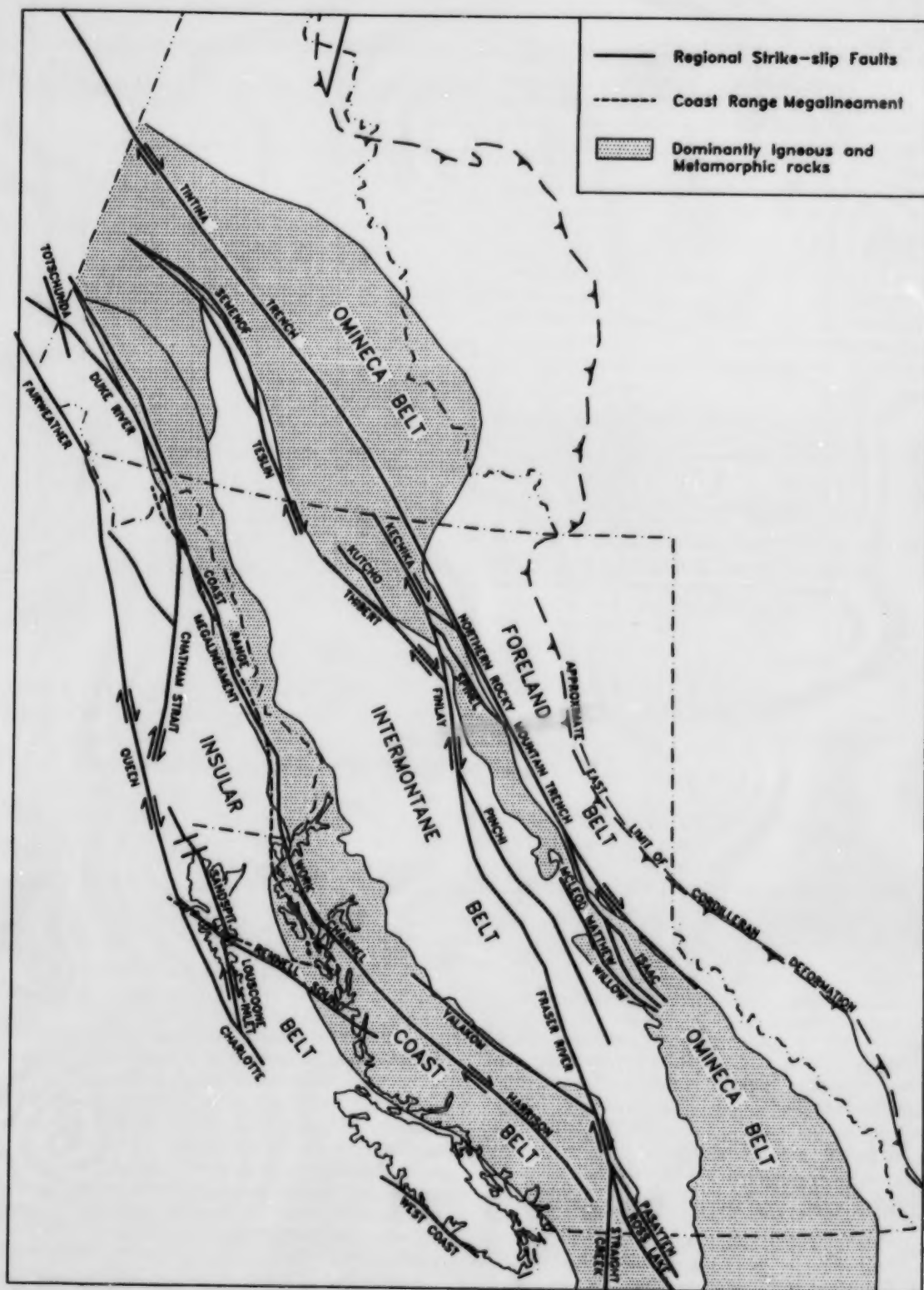


Figure 2-6. Schematic section illustrating the timing of amalgamation of terranes that comprise the Intermontane and Insular superterranes and the times of accretion or docking of major Cordilleran terranes with the North American plate (modified after Monger *et al.*, 1982).



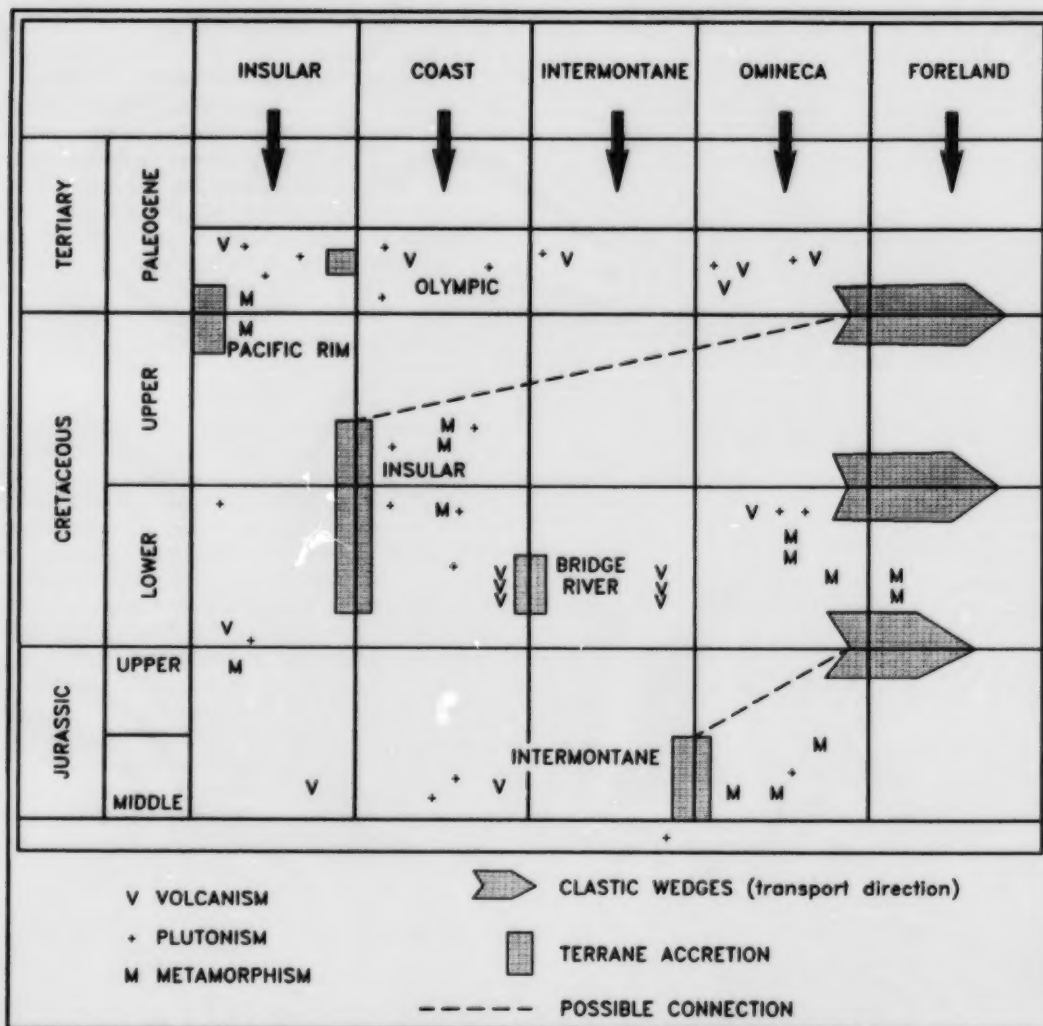


Figure 2-8. Schematic chart, modified after Gabrielse and Yorath (1989), showing possible connections between the timing of docking of accreted terranes, volcanism and plutonism in the various tectonic belts and deposition of related clastic wedges in the Foreland Belt.

ation for mineral deposition by producing deeply penetrating fracture systems and by generating heat flow and magmas that favour formation of large hydrothermal systems.

PLATE TECTONICS AND MINERAL DEPOSIT SETTINGS

Many mineral deposits are closely related to consuming-margin, island-arc processes (Figure 2-10). Volcanogenic massive sulphide, platinum group element-bearing magmatic deposits, skarn, propylitic gold (Panteleyev, 1988), porphyry deposits, mesothermal to transitional vein and

replacement deposits, and epithermal veins formed in the late Triassic and Jurassic island-arcs of Quesnellia, Stikinia and Wrangellia.

Docking events produced deposits related to granitic intrusions and terrane boundaries. Terrane boundaries are characterized by Motherlode-type mesothermal gold deposits hosted in disrupted ophiolite or mixed oceanic rock assemblages. Mineralization in these settings is generally related to collision-generated plutonism that is significantly younger than the hostrocks.

Post-docking granite and volcanic-related mineralization includes polymetallic veins, mantos, molybdenum porphyries, skarns and epithermal deposits.

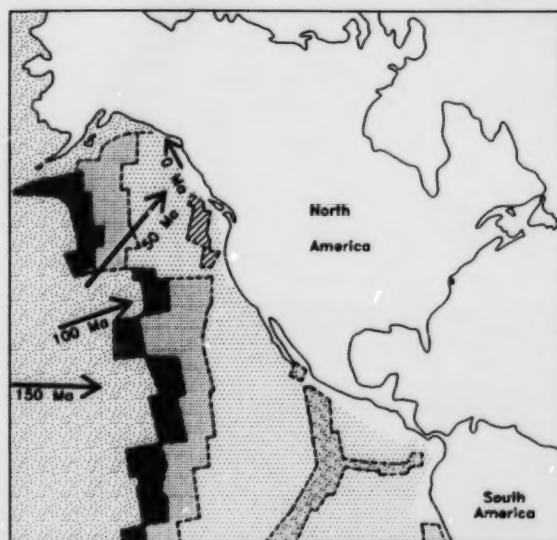


Figure 2-9. Schematic map showing variations in relative movement vectors between the North American and Pacific plates during the last 150 million years. The lengths of the vector arrows depict relative rates of movement. The patterns show magnetic reversals (after Engebretson, 1985).

DEPOSITS IN OCEANIC AND ISLAND ARC SETTINGS

VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS

Deposits in oceanic and island-arc settings formed mainly before or during terrane amalgamations. During extensional events, some volcanogenic massive cupriferous pyrite Cyprus-type deposits formed on or close to the sea floor, either at ocean ridges or in back-arc settings, with or without generation of oceanic crust (Figure 2-10). Examples in the Alexander Terrane (Figure 2-11) are Anyox (Alldrick, 1986) and perhaps Windy Craggy (MacIntyre, 1986); in Quesnellia, an example is Chu Chua (Aggarwal and Nesbitt, 1984). In compressional, island-arc settings, volcanogenic polymetallic massive sulphide deposits of the Kuroko type formed in the volcanic arcs and are also found in remnant arcs. Examples are Britannia (Stone and Payne, 1982) in Wrangellia, Kutcho Creek (Bridge *et al.*, 1986) in Stikinia, and Rea in Quesnellia (Hoy and Goutier, 1986). Sediment-hosted, Besshi type, copper-zinc massive sulphides form in extensional settings in both fore-arc and back-arc basins. Examples are perhaps Granduc and Windy Craggy in the Alexander Terrane and Goldstream in the Omineca Belt (Höy, 1982).

MAGMATIC DEPOSITS

Metal sulphides are found locally as segregations or differentiation products in magmatic, often ultra-

mafic, rocks. Chromite schlieren are found in Alpine ultramafic complexes. Zoned Alaskan ultramafics, like Tulameen in southern British Columbia, carry platinum group elements (PGE) with chromite layers or sulphide segregations. Nickel, copper and cobalt sulphides occur with interesting levels of PGE in layered ultramafic bodies, like Wellgreen in Yukon. The former Giant Mascot mine, near Hope in southern British Columbia, produced nickel and copper with byproduct PGE from a satellitic stock of the calcalkaline Spuzzum intrusions. The stock is zoned from pyroxenite through to quartz diorite. In the Franklin Camp, near Greenwood in south-central British Columbia, sulphide-rich blebs in Coryell augite syenites carry interesting PGE values.

PORPHYRY COPPER DEPOSITS

Porphyry copper deposits have been the source of most of the copper and molybdenum and more than 40 per cent of the gold produced in British Columbia (Figure 2-12). Porphyries carrying significant gold fall within both the alkaline and calcalkaline classes (Drummond and Godwin, 1976, p.59), whereas those with molybdenite are mainly calcalkaline. Generally, important gold values occur only in porphyry deposits in volcanic settings or with high level porphyry intrusions (McMillan and Panteleyev, 1988). Thus the alkaline Copper Mountain, Afton, Galore, Cariboo Bell, QR and Schaft Creek deposits and the calcalkaline Fish Lake and Island Copper deposits contain economically important amounts of gold. Deeper-level, plutonic hosted porphyry deposits, like those in Highland Valley, have economically important amounts of molybdenum, some silver, but little gold. This accords well with observations in the southwest Pacific (Sillitoe, 1990) that only porphyries related to high-level plutons (1.5 to 4 kilometres depth) have high gold signatures. Similarly, Cox and Singer (1988) show estimated depths of 0.4 to about 2 kilometres for gold and gold-molybdenum porphyry deposits.

Porphyry deposits characteristically form from large, granite-related hydrothermal systems, and mineralization is mainly fracture controlled. Copper Mountain and Afton (Barr *et al.*, 1976) are alkalic, gold-bearing porphyries in the Intermontane Superterrane. Island Copper (Cargill *et al.*, 1976) in the Insular Superterrane is a subvolcanic, calcalkaline example. Island Copper gold values are highest at the top of the mineralized zone, in an area of advanced argillic alteration, but values are also important in the core of the deposit and in the propylitic alteration zone.

SKARN DEPOSITS

Skarn deposits have been important producers of copper, tungsten, iron and gold in the Canadian Cordillera (Figure 2-13). There are more than 100 gold-enriched skarns (those that carry in excess of 1 ppm

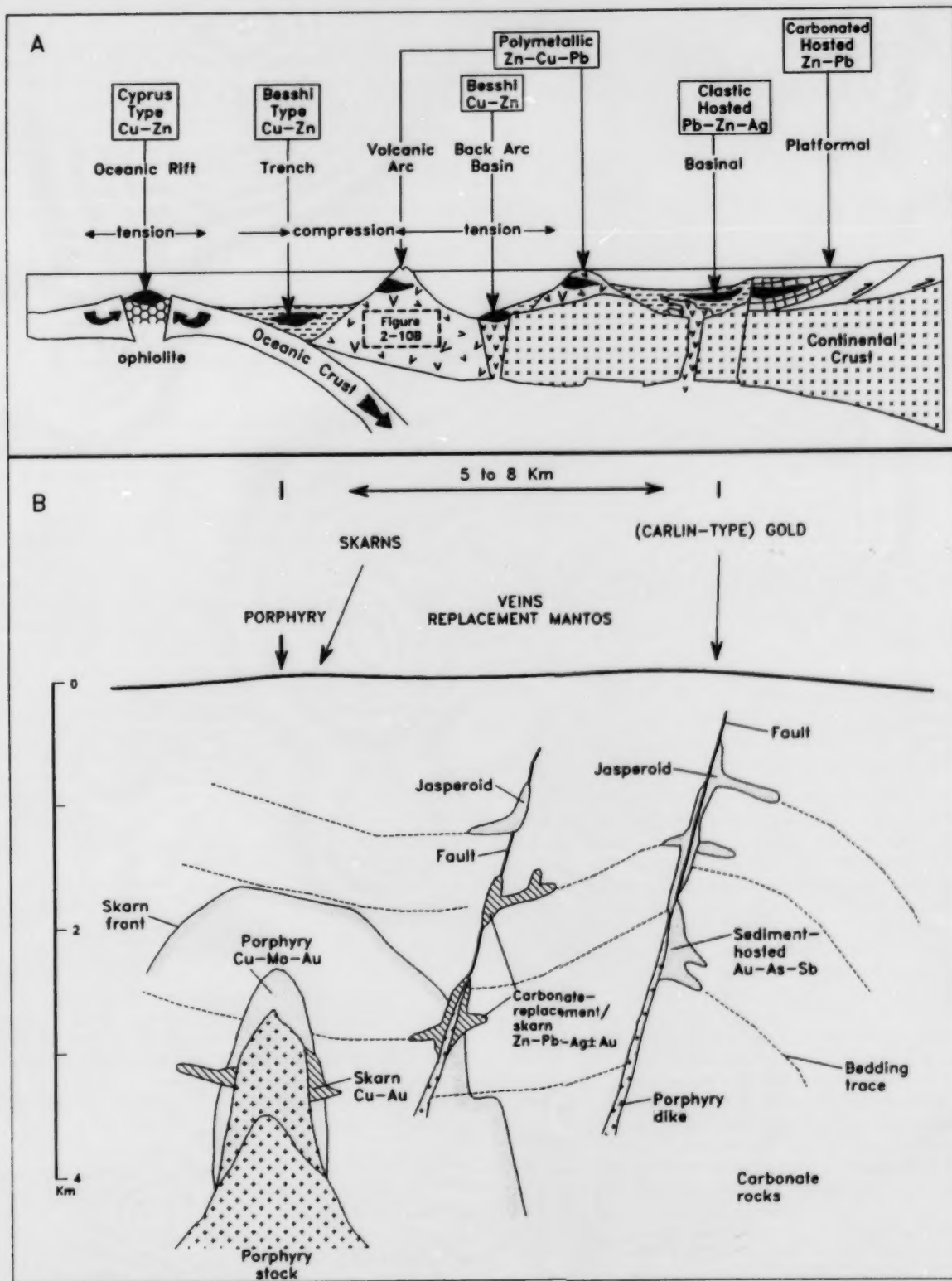


Figure 2-10. Schematic diagrams showing associations of mineral deposits with plate tectonic environments for (A) near surface volcanogenic massive sulphide, Sedex and platformal base metal deposits (modified after Hutchinson, 1980) and (B) subvolcanic porphyry, skarn, vein, replacement, manto and Carlin-type gold deposits (after Sillitoe and Bonham, 1990).



Figure 2-11. Distribution of major volcanogenic massive sulphide deposits of the Kuroko polymetallic, Cyprus cupriferous pyrite and Besshi copper-zinc types in British Columbia (after Høy, this volume).

Au) in island-arc settings in British Columbia. Wrangellia features copper-iron skarns, like those on Vancouver Island at Kennedy and Benson lakes, and on the Queen Charlotte Islands at Jedway. Stikinia and Quesnellia have copper-iron skarns, like Craigmont, and gold skarns like those in the Hedley camp (Ray and Dawson, 1992). Intrusions into miogeoclinal North American rocks, especially in northeastern British Columbia and Yukon, generated tungsten, molybdenum and, locally, tin-bearing skarns.

The copper and iron skarns are generally related to primitive, calcalkaline, I-type intrusions emplaced into limy sediment successions. Both intrusions and country rock may be skarnified. In contrast, tungsten, molybdenum and tin skarns are related to more evolved, S-type intrusions, which have a crustal component.

GOLD DEPOSITS IN ISLAND-ARC AND BACK-ARC SETTINGS

Mesothermal Deposits

Gold deposits are also common in island-arc environments. The vein mineralogy and types of alteration are similar to those in oceanic hostrocks (discussed later) but base metal concentrations in the veins tend to be higher, and mixed volcanic and

sedimentary rocks comprise the wallrocks. In the Intermontane Superterrane, the Rossland Camp (Fyles, 1984) in Quesnellia and the Golden Bear deposit in Stikinia (Oliver and Hodgson, 1989) are examples. At Rossland, copper-gold veins consist of chalcopyrite and pyrrhotite with lenses of quartz and calcite. The deposits are localized in an area that is characterized by large-scale faults with associated serpentinite bodies, and by extensive areas of hornfelsic alteration within a succession of Jurassic shoshonitic volcanics, related monzonite and syenite

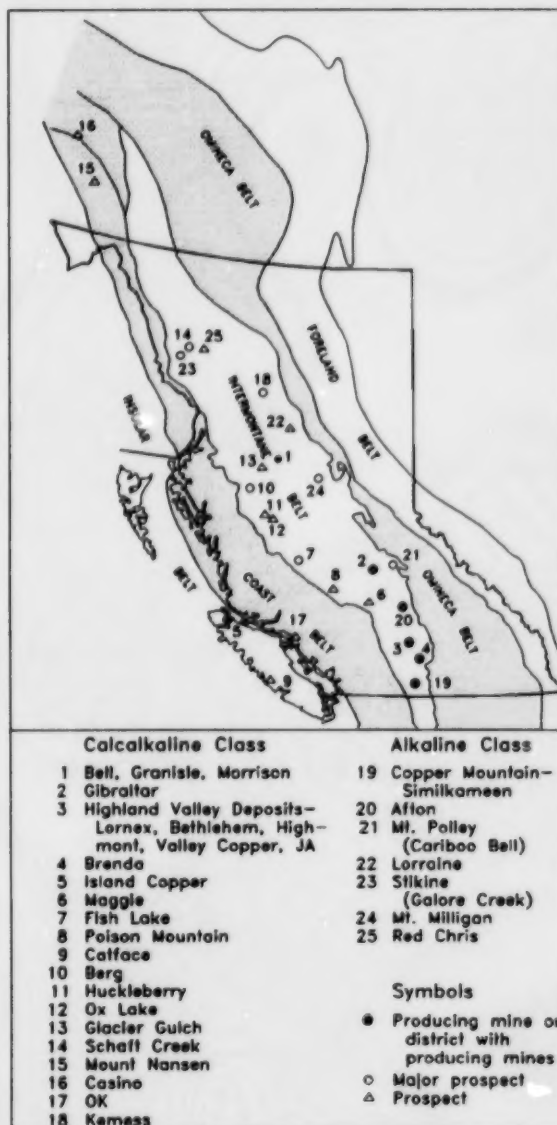


Figure 2-12. Distribution of calcalkaline and alkaline-class porphyry copper-molybdenum and copper-gold deposits in the Canadian Cordillera (modified after McMillan and Panteleyev, 1988).

intrusions, and many dikes (Fyles, 1984). Tertiary porphyry molybdenum deposits on Red Mountain, and bonanza epithermal gold-vein deposits like those in Little Sheep valley to the south, overprint the mesothermal system.

Epithermal Deposits

Epithermal deposits in the Canadian Cordillera are associated with subaerial to submarine, felsic to

intermediate volcanic rocks in areas of block faulting, with caldera structures, or associated with stratovolcanos. Extensional environments, either in continental, island-arc or back-arc settings, are likely target areas for these epithermal deposits. Those in the Toodoggone area in the Stikine Terrane of north-central British Columbia are Early Jurassic in age but have all the characteristics of younger epithermal deposits (Panteleyev, 1988). The best of the known deposits in the Toodoggone belt — Baker,

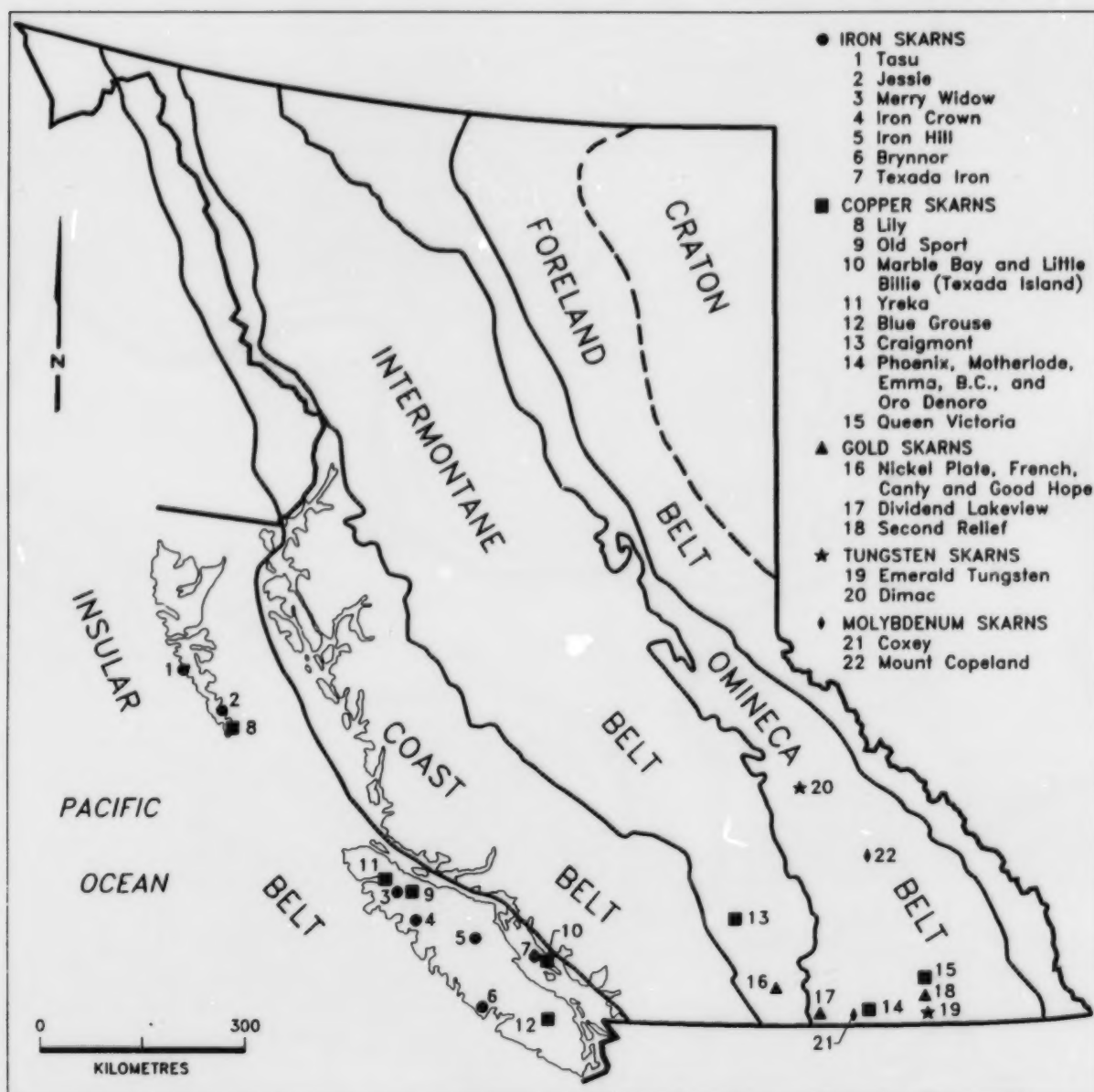


Figure 2-13. Distribution of gold and precious metal-enriched skarn deposits in the Canadian Cordillera (after Ettlinger and Ray, 1989).

Cheni and Al — lie along its volcanic-plutonic axis. Cretaceous successor-basin sediments that onlap the belt from the west have potential for paleoplacer deposits (Eisbacher, 1974) .

A large vertical range within the hydrothermal systems is exposed by block faulting in the Toodoggone area. The shallowest levels are represented by siliceous, alunite-clay cappings and fossil hot-spring acid-sulphate alteration zones (low pH acid caps) and some, like Al, have associated gold-barite min-

eralization. The main epithermal deposits are base metal poor amethystine quartz or base metal bearing quartz-carbonate veins. At deeper levels, porphyry copper-molybdenum deposits, like the Porphyry Pearl prospect, are also enhanced in precious metals. Expected arsenic and antimony-rich cupriferous pyritic gold-silver deposits (hot and/or deep acid-sulphate high sulphidation types) with enargite-alunite assemblages are apparently 'missing' in the Cordillera; it is likely that they are present but have

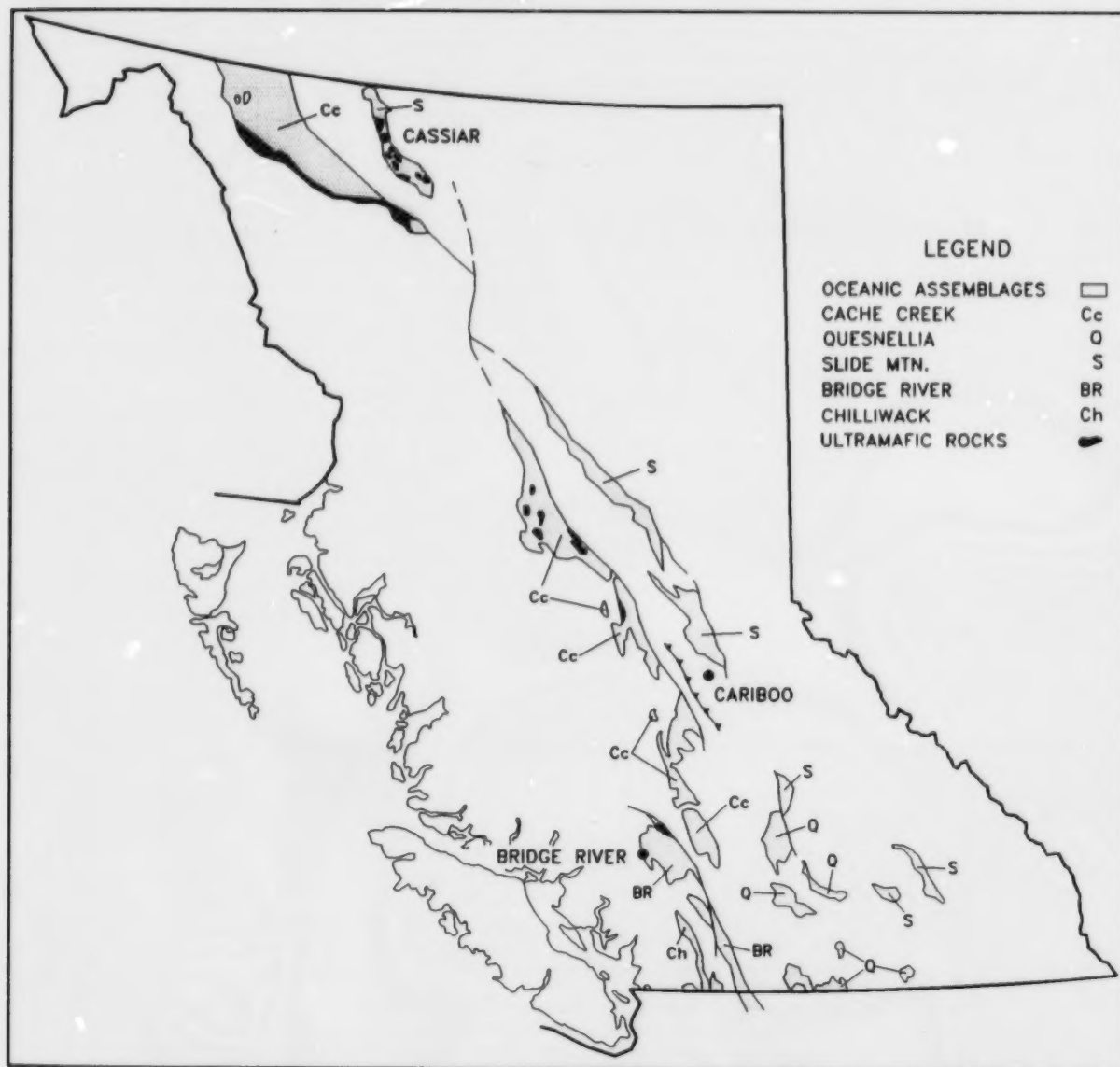


Figure 2-14. Distribution of oceanic terranes along major structures in British Columbia; oceanic rocks occur in the Cache Creek and Slide Mountain terranes, and in Quesnellia and Stikinia. Ultramafic rocks associated with these rocks are also shown (modified after Monger, 1972).

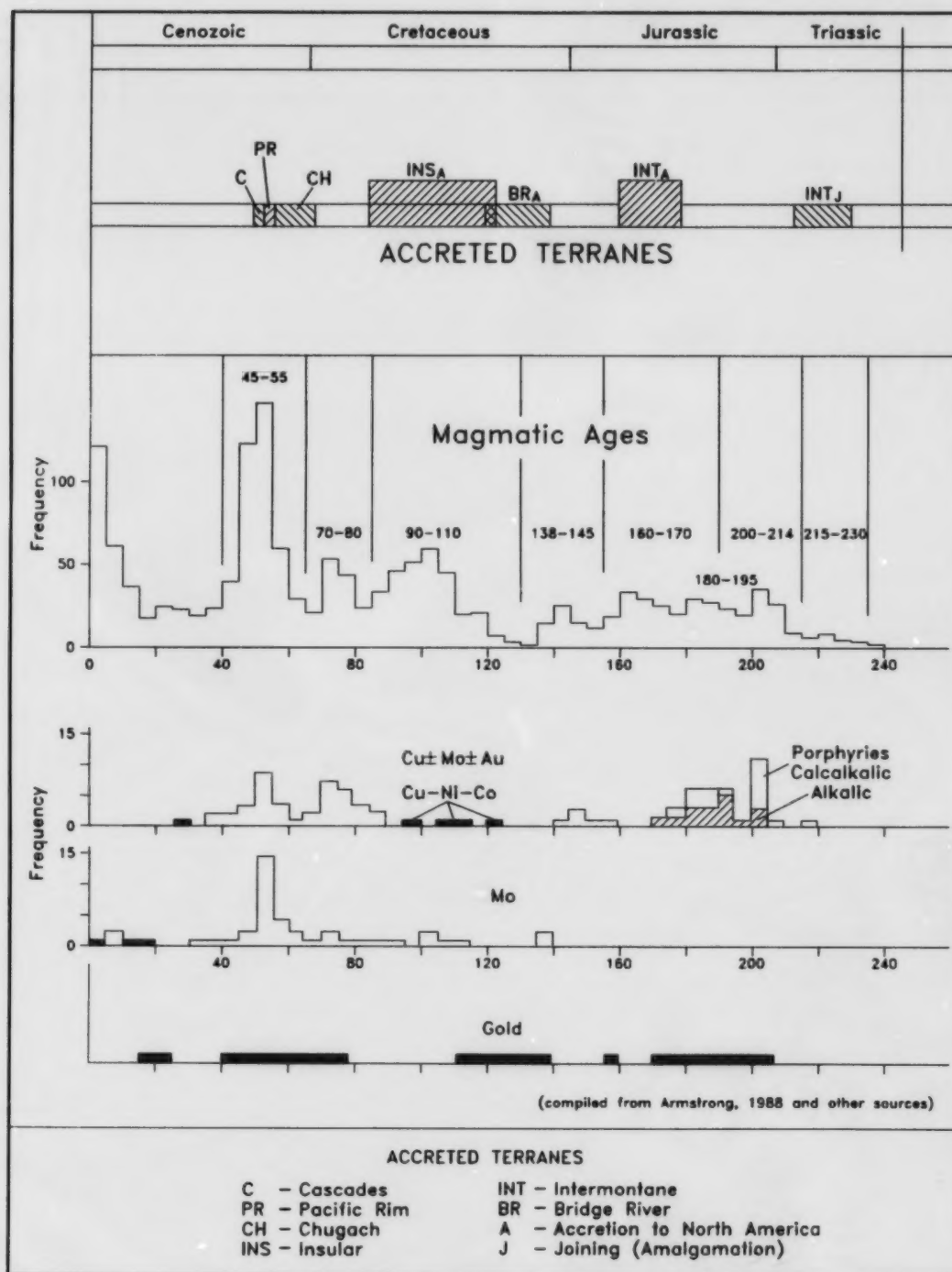


Figure 2-15. Chart comparing dated magmatic events, and timing of amalgamation and accretion of the major terranes that comprise the Cordillera, with the timing of copper, molybdenum and gold mineralizing events in the Canadian Cordillera (compiled from Armstrong, 1988, and other sources).

been overlooked (Equity is too deep but comes close to fitting the criteria).

Transitional Epithermal to Mesothermal Deposits

Transitional deposits in island-arc settings have aspects of both epithermal and mesothermal or even porphyry copper deposits. Examples are found in mining camps such as Stewart and Sulphurets in the Stikine Terrane of northwestern British Columbia. Mineralization is Jurassic and, within this consuming-margin setting, related to subvolcanic plutons and dikes cutting submarine to subaerial island-arc volcanic and epiclastic rocks (Alldrick, 1985). The ore shoots are variably interpreted to be syngenetic and stratiform (Meade, 1986) or epigenetic and cutting stratigraphy (Alldrick, 1985). There are also Tertiary silver-lead-zinc deposits, like Silverado, in the area that are related to emplacement of the Coast plutonic suite. Plotted lead isotope analyses form separate clusters for Jurassic and Tertiary events. Lead in the Jurassic deposits is from a volcanic source, whereas that in the Tertiary deposits has a crustal component (Alldrick *et al.*, 1987).

Vertical mineral zoning is a characteristic of the camp. Deposits formed at the shallowest depths are relatively silver-rich and epithermal, whereas the deepest are gold-rich and mesothermal; other deposits are transitional in character. The Silbak-Premier deposits mined to a depth of about 100 metres were true bonanza ores, with gold, electrum, argentite, polybasite, and some native silver (Bacon, 1978). Mesothermal deposits include the deepest Silbak-Premier orebodies and Scottie Gold. At Scottie, gold-silver mineralization occurs in a series of parallel veins of massive pyrrhotite and pyrrhotite-pyrite in andesitic lapilli tuff and tuff breccia.

DEPOSITS IN OCEANIC HOST ROCKS

Deposits in oceanic hostrocks often are situated (Figure 2-14) at or near major, tectonic boundaries that may be terrane boundaries. They do not appear to be arc-related. Ore zones are structurally controlled and mineralization is generally in veins and tension gashes generated by transverse faulting. The hostrocks, often dismembered ophiolites or assemblages consisting of mixed island-arc and marine clastic rocks, generally are intruded by felsic to mafic plutonic rocks and spatially associated with serpentinites. For the Mother Lode District, Taylor (1992) argues that the host fault system persisted for at least 30 million years and originated 10 to 15 million years before gold veins formed (Bohkle and Kestler, 1986).

In British Columbia, the Bridge River gold camp produced about 130 tonnes (4.1 million ounces) of gold, predominantly from the Pioneer and Bralorne

mines along the Cadwallader-Fergusson-Empire fault system. The Bridge River Terrane (Tipper, 1981) is a fault-bounded slice of oceanic rocks that consists of basalts, ribbon cherts and argillites of the Permian to Jurassic Bridge River Complex; calcareous argillite, and generally pillowed greenstones of the late Triassic Cadwallader Group; and the Shulaps ophiolite complex. In the area of the deposits, Paleozoic Bralorne quartz diorite (270 Ma), is cut by a large, dike-like body of soda granite of similar age. Subsequent Cretaceous, premineral albitite bodies (91 Ma) and then postore porphyry dikes (85 Ma) intrude the older rocks (Leitch and Godwin, 1988). Thus the mineralizing event was in Late Cretaceous time, shortly after the Insular Superterrane collided with North America, and apparently is related to granites emplaced during formation of the Coast Plutonic Complex. Woodsworth *et al.*, (1977) concluded that mineralization post-dated major transverse movement on the fault system, and the system is pinned by the 70 Ma Coast intrusions (Glover and Schiarizza, 1987). Metal zoning outward from the Coast intrusions (Woodsworth *et al.*, 1977) defines a northeast trend that may represent a premineral fracture zone. A central gold-silver-arsenic-tungsten-molybdenite zone is fringed by antimony-silver-gold-arsenic, mercury-antimony with or without gold, then mercury zones. Nesbitt *et al.*, (1986) argue that stibnite and cinnabar formed at successively shallower depths and in cooler areas in the vein system. Mineralization apparently spanned a considerable time interval. The main gold veins formed between 91 and 85 Ma, but some veins cut Tertiary dikes. Northeast of the Bridge River camp, along the trend, deposits become progressively younger. The Poison Mountain porphyry copper-molybdenum-gold deposit is about 58 Ma (Glover *et al.*, 1988) and further northeast the Blackdome epithermal gold deposit is 51 Ma (Faulkner, 1986). Consequently, the zoning may be more complex than it first appears and it could represent overlapping of several events along a long-lived northeast-trending structural zone.

At Cassiar, in northern British Columbia, the general lithological setting of gold deposits at and around the Erickson Mine is similar to that of the Bridge River Camp. Unlike the Bridge River deposits, Cassiar gold veins, like the Cassiar asbestos deposits of similar age (Nelson and Bradford, 1989), occur within thrust sheets near the base of the obducted Sylvester allochthon. In Cassiar, most gold mineralization occurs within late Paleozoic to Triassic oceanic rocks of the Slide Mountain Terrane within the allochthon. Sketchley *et al.* (1986) dated the mineralizing event at 129 Ma.

The setting of gold mineralization in the Atlin Camp is also similar to that of the Bridge River area, however, mineralization in Atlin is older, at 160 Ma. The auriferous veins are hosted in listwanite-altered oceanic rocks of the Cache Creek terrane (Ash and Arksey, 1990).

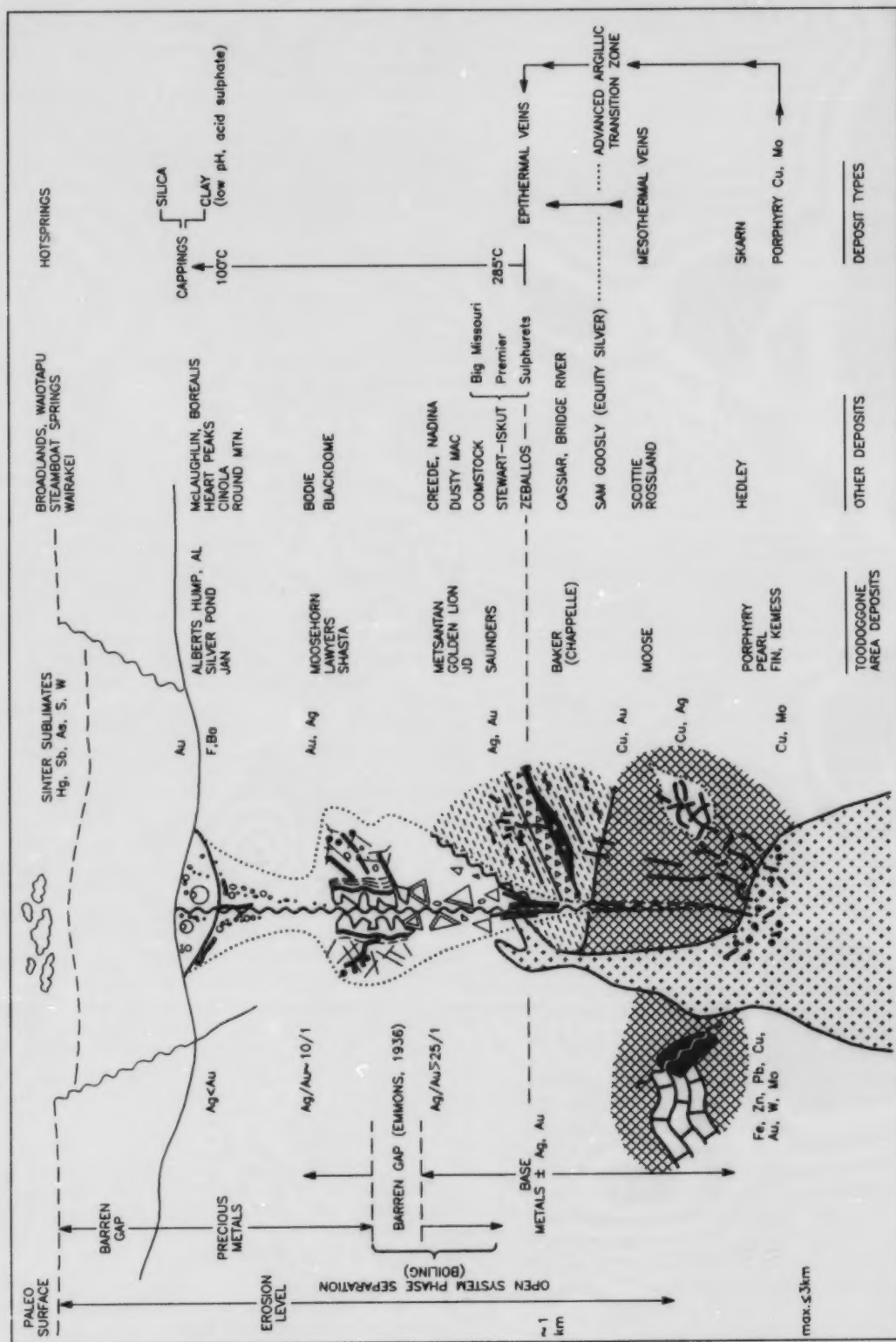


Figure 2-16. A depth-zoning scheme for the Mesozoic Toodoggone epithermal gold through to porphyry copper-gold camp that illustrates variations in style of mineralization with depth. It attempts to relate these variations to metal abundances and known mineral deposits, and compares these deposits with deposits elsewhere in the Cordillera and the world (after Panteleyev, 1968).

SUMMARY

DEPOSITS IN NORTH AMERICAN ROCKS

Rifting dominated metallogeny in North American miogeoclinal rocks prior to accretion of the accreted terranes. The most important deposits are Proterozoic sediment-hosted lead-zinc-silver massive sulphides, characterized by the Sullivan deposit, and Devonian clastic-hosted, baritic lead-zinc-silver massive sulphides of the Gataga area and the Selwyn basin. Mississippi Valley type lead-zinc deposits like those at Robb Lake occur in Devonian platform limestones. Sedimentary industrial mineral deposits (barite, gypsum, phosphates) are also important.

Syn and postaccretionary deposits in miogeoclinal rocks include molybdenum-tungsten porphyries and skarns, tungsten-tin skarns, silver-lead-zinc mantos, asbestos deposits, like Cassiar, and mesothermal gold deposits, like Erickson. Postaccretionary epithermal gold in basins associated with strike-slip faults may become important. For example, Grew Creek, an Eocene gold-silver deposit, lies in a graben within the Tintina Trench. Mineralization occurs in quartz stockworks mainly in the tuffs adjacent to a quartz feldspar porphyry emplaced along a fault contact between rhyolitic tuff and fluvial sediments.

DEPOSITS IN ACCRETED ROCKS

Many deposits in the accreted Canadian Cordillera are related to plate tectonic processes — either island-arc development, or plate collision and accretion combined with more localized heating and magmatic events (Figure 2-15). Island-arc deposits are generally related to magmatism resulting from subduction at consuming margins in volcanic-arc or perhaps back-arc settings where porphyry deposits, skarns, mesothermal, transitional and epithermal gold deposits and volcanogenic massive sulphides form. Massive cupriferous pyrite deposits (Cyprus type) formed at oceanic spreading centres, in continental-border rifts, like the modern Guaymas basin, and possibly in back-arc basins.

Periodic accretionary events, marked by closure of ocean basins, led to welding or obduction of oceanic crustal rocks against North American or island-arc assemblages. The Slide Mountain and Cache Creek terranes at the leading edge of the Intermontane Superterrane, and the Bridge River Complex at the leading edge of the Bridge River Terrane, are examples. In the Cassiar, Atlin and Bralorne areas, plate collision led to faulting, obduction of dismembered ophiolite sequences onto adjacent terranes, plutonism and formation of mineral deposits. Terrane-boundary faults provided permeability and tapped deeply into the crust. Heat and plutonism generated large-scale hydrothermal systems that gave rise to mesothermal gold and related deposits. These ores were deposited above the brittle-ductile transition

zone in the crust from low salinity, CO_2 -charged ore fluids that were isotopically modified by wallrock interaction (Nesbitt *et al.*, 1986).

Early Cretaceous mesothermal gold deposits that are hosted by oceanic rocks lie along the length of the North American Cordillera — from Cassiar, in northern British Columbia, to the Mother Lode district in California. This major metallogenic event may record a significant shift in movement vectors between the Pacific and North American plates. Similarly, the younger Bridge River gold veins are related to transcurrent faulting, suggesting docking vectors oblique to the plate boundary. Metals in the camp are zoned, apparently outward from the collision-generated Coast Range intrusions.

In island-arc settings, gold-bearing deposits are mesothermal to epithermal. Most are associated with either I-type, subduction-related intrusions or high-potassium alkalic to calcalkaline back-arc or marginal basin volcanics and intrusives.

Strike-slip faults and other deep fractures with related zones of high heat-flow, mantle hot spots, or other thermal events, produced post accretionary vein, skarn and manto deposits.

CONCLUSIONS

Similar plate tectonic processes occurred at intervals in the history of the Cordillera. Consequently, many of the deposit types are found in both older and younger rocks. Erosional levels are critically important to the types of deposits exposed (Figure 2-16). Some, such as porphyries, skarns and epithermal deposits, are not known in Paleozoic rocks, whereas others, such as mesothermal deposits with associated listwanite alteration, are unknown in Tertiary rocks. Metal sources, the chemistry of the magma source-rock, permeability, faults, a heat source to drive hydrothermal convection, and the chemistry of both the ore fluid and the country rock all play their role. Tectonic setting is important in defining areas favorable for mineralization, but the other factors control the locations and types of ore deposits formed.

There is a spectrum of deposit types between porphyry, skarn and mesothermal through to epithermal and surface-formed deposits. Telescoping occurs. In the Stewart Camp, for example, epithermal deposits are unusually rich in base metals and silver values are high, which are general characteristics of mesothermal deposits. Perhaps this indicates that the ore fluids were saline and derived from sea water, not meteoric water. Mineralizing events are multicyclic. Younger phyllic and advanced argillic alteration overprint early propylitic alteration in porphyries. Strike-slip faults and other deep fractures with related zones of high heat flow, mantle hot spots or other thermal events produced post-accretionary vein, skarn and manto deposits. The depth-zoning model (Panteleyev, 1988) displays probable settings and characteristics of Cordilleran deposits (Figure

2-16). It illustrates variations that can be expected in a vertical section through a major composite hydrothermal system, and we recognize these variations in deposits in British Columbia.

ACKNOWLEDGMENTS

Materials in this report draw heavily on the work of the many geoscientists who have studied and are studying the mineral deposits, tectonics and geology of the Cordillera. It also incorporates information and ideas from work done elsewhere. The Reference list acknowledges some of these geoscientists, but not all. This report would have been impossible to produce without their information. Thanks are also extended to John Newell, for his thoughtful comments, and to external reviewers Al Sinclair and Jim Monger for valued input and suggestions to improve the manuscript.

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SEDEX — SEDIMENTARY-EXHALATIVE DEPOSITS

by D.G. MacIntyre

INTRODUCTION

Sedimentary-exhalative or SEDEX massive sulphide deposits are an economically important source of lead, zinc and silver both in the Canadian Cordillera and worldwide. These deposits are typically found in fault-controlled, intracratonic basins and miogeoclines of Middle Proterozoic through Middle Paleozoic age. They are characterized by thin laminae to massive beds of pyrite, pyrrhotite, sphalerite and galena and are found in a variety of host rocks including carbonaceous cherts, fine-grained turbidites and shelf carbonates. This class of mineral deposit has been reviewed in detail by several authors including Large (1980, 1981, 1983), Finlow-Bates (1980), Gustafson and Williams (1981), Russell *et al.* (1981), Morganti (1981), Came and Cathro (1982) and others. Much of the information presented here is derived from these earlier reviews.

DEPOSIT CHARACTERISTICS

Sedimentary-exhalative deposits are mineralogically simple with pyrite and/or pyrrhotite, sphalerite and galena the predominant sulphide minerals. Barite is also a major component of many deposits, especially those of Devonian-Mississippian age (Table 3-1). There is often a well-developed zoning of sul-

phide minerals both within a single bed and the deposit as a whole. Generally, galena and sphalerite predominate near the base of the deposit and adjacent to an exhalative vent whereas barite is usually found overlying or peripheral to the sulphide facies. Zinc is more widely dispersed than lead giving rise to decreasing Pb:Pb+Zn ratios away from the vent area. Although copper is generally in low abundance within sedimentary-exhalative deposits, some do have significant chalcopyrite in genetically related stockwork zones (*e.g.* Mount Isa) or overlying stratiform massive sulphides (*e.g.* Rammelsberg). Deposits with volcanic rocks in the host succession tend to contain more copper although there are numerous exceptions to this rule. The presence of copper may reflect higher temperatures of ore formation rather than differences in hostrock composition.

Barite is a very common component of this class of deposits and there is often a complete gradation from predominantly massive sulphide with minor barite, through interbedded barite and sulphide to barren barite. This variation is probably due to such factors as amount of reduced sulfur and oxygen available at the site of deposition, temperature and composition of the metalliferous brines and availability of barium within the marine sedimentary column. Because bedded barite deposits are often

TABLE 3-1

World-Class Sedimentary Exhalative Massive Sulphide Deposits

Deposit	Age	Paleotectonic Setting	Host Rocks	Type	Tonnes (millions)	Zn %	Pb %	Ag g/t	Cu %	Barite (in ore)
Mount Isa, Australia	M. Proterozoic	Leichhardt R. Trough	dolomitic shales, siltstones	1B	88.6	6.3	6.9	149		low
McArthur River, Australia	M. Proterozoic	Batten Trough	dolomite, evaporite, siltstone	1B	190.0	9.5	4.0	45		low
Sullivan, Canada	M. Proterozoic	Purcell Basin	basinal turbidites	1A	155.0	5.7	6.6	7		low
Faro, Canada	Cambrian-Ord.	Selwyn Basin	graphitic phyllites	1A	57.6	4.7	3.4	36		mod.
Howard's Pass, Canada	Early Silurian	Selwyn Basin	dolomitic shales, chert	1B	125.0	5.4	2.1			low
Jason, Canada	Late Devonian	Selwyn Basin	shales and turbidites	1A	15.5	6.6	7.1	79		mod.
Tom, Canada	Late Devonian	Selwyn Basin	silty and cherty argillite	1A	15.7	7.0	4.6	49		mod.
Cirque, Canada	Late Devonian	Kechika Trough	cherty argillite, shale	1A	32.2	7.9	2.1	48		high
Rammelsberg, Germany	Dev.-Miss.	Variscan Trough	shales, siltstones	1A	22.0	19.0	10.0	120	2.00	low
Meggen, Germany	Dev.-Miss.	Variscan Trough	shales, siltstones	1A	50.0	10.0	1.3	3	0.02	mod.
Red Dog, Alaska	Mississippian	Kuna Formation	black sil. shale and cherts	1A	85.0	17.1	5.0	82		mod.
Tynagh, Ireland	Mississippian	Central Midlands Basin	shelf carbonates	1C	8.6	5.5	7.0	81	0.58	low
Silvermines, Ireland	Mississippian	Central Midlands Basin	shelf carbonates	1C	12.9	6.8	2.6	25		low
Navan, Ireland	Mississippian	Central Midlands Basin	shelf carbonates	1C	69.9	10.1	2.6	11		low

Deposit Types (this paper): 1A — clastic hosted, starved basin; 1B — mixed carbonate-clastic, shallow marine; 1C — shelf carbonate hosted

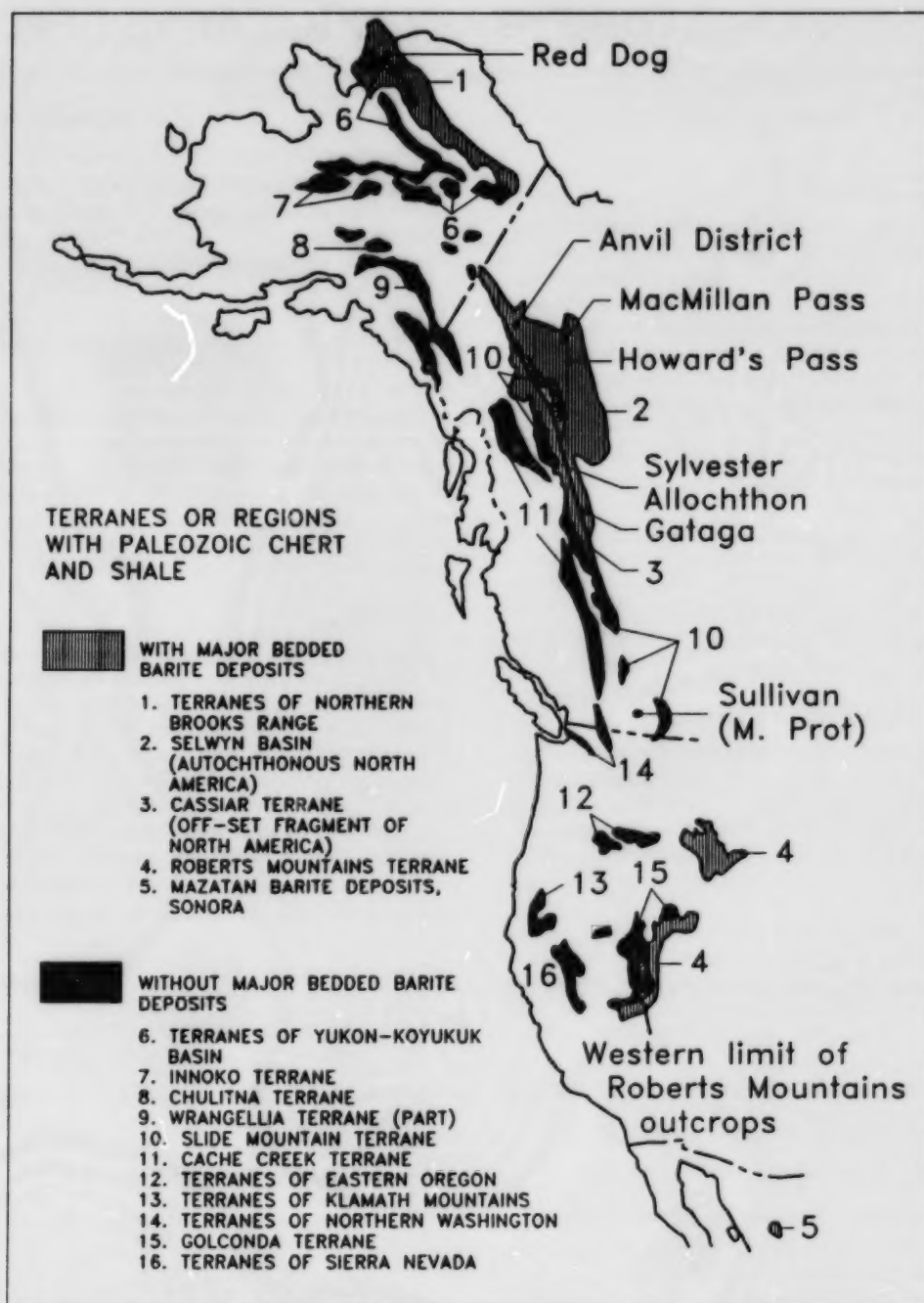


Figure 3-1. Location of major sedimentary exhalative deposits and shale basins in the North American Cordillera. After Murchey and Madrid, 1987.

found in the same area as massive sulphide and barite-sulphide deposits, they are also included in this compilation.

Many ancient deposits have stockwork zones cutting footwall rocks suggesting the source of mineralizing fluids lies stratigraphically below the deposits. The most popular theory is that the mineralizing fluids were derived by dewatering of basinal sediments in response to rifting, subsidence and elevated heat flow. The fluids were channeled to the sea floor along permeable sedimentary horizons and intersecting fault zones.

In almost all sedimentary-exhalative deposits there is some evidence for synsedimentary faulting. This is consistent with their regional distribution in both time and space, which indicates a very close association with major episodes of crustal extension. Locally, these rifting events were accompanied by igneous activity in the form of submarine flows and emplacement of subvolcanic sills. In some cases volcanic rocks constitute a significant proportion of the host succession and the deposits can be classified as either volcanogenic or sedimentary-exhalative depending on one's bias. In any case, there is most likely a complete gradation from strictly sediment-hosted to predominantly volcanic-hosted end members with the volume of volcanic rocks directly related to the amount of crustal attenuation taking place.

DISTRIBUTION IN TIME AND SPACE

Sedimentary-exhalative deposits are found worldwide in Proterozoic and Paleozoic basinal and platform facies marine sedimentary rocks (Table 3-1). There are no known major Mesozoic or Cenozoic deposits of this type. Some of the best known and most extensively studied deposits are Mount Isa and McArthur River (HYC) in Australia, the Meggen and Rammelsberg deposits in West Germany, and the Tynagh, Navan and Silvermines deposits in Ireland. Mount Isa and the Irish deposits are hosted by shallow water carbonate-rich sediments that were deposited near active growth faults. The German deposits on the other hand were deposited in restricted sec-

ond and third-order marine basins. World class sediment hosted exhalative massive sulphide and barite deposits are also found in the North American Cordillera (Figure 3-1, Table 3-1).

CANADIAN CORDILLERA DEPOSITS

Sedimentary-exhalative deposits are the most important source of zinc and lead in the Canadian Cordillera (Carne and Cathro, 1982). Two of the largest producers are Faro in the Yukon Territory and the Sullivan mine in southeast British Columbia. Another large deposit is the Red Dog in northeast Alaska which was recently brought into production by Cominco Ltd. This exceptionally high-grade deposit contains 85 million tonnes of ore averaging 17.1 per cent zinc, 5 per cent lead and 82 grams per tonne silver.

In the Canadian Cordillera, major prospects and potential producers include deposits of the Anvil, Howard's Pass and MacMillan Pass districts of the Yukon and the Cirque or Stronsay deposit in northeast British Columbia. These and other major sedimentary-exhalative deposits are listed in Tables 3-2, 3-3, and 3-4 and their locations are shown in Figure 3-2.

In the Canadian Cordillera, sedimentary-exhalative zinc-lead and barite deposits are found in pre-accretion rocks of ancestral North America and the related Cassiar, Kootenay and Monashee terranes. The boundaries of these terranes and the distribution of sedimentary-exhalative deposits is shown in Figure 3-2. The host terranes are discussed in the opening chapter of this volume.

Terranes hosting sedimentary-exhalative deposits are characterized by supracrustal rocks of Proterozoic to Late Paleozoic age that overlie a crystalline basement of probable Archean age. The clastic detritus was largely derived from the North American craton and deposited in intracratonic basins or as a prograding, westward-thickening miogeoclinal clastic wedges (Figure 3-3). Rifting and crustal subsidence along the continental margin controlled the distribution of sedimentary facies and the formation of sedimentary-exhalative deposits.

TABLE 3-2

Middle Proterozoic Sedimentary Exhalative Deposits

Map No.	Terrane	Tectonic Element	Dep. Type	Deposit Name	Commodities	Million Tonnes	Zn %	Pb %	Cu %	Ag g/t	Au g/t	Host Rocks
1	NA	Mackenzie Platform	1A	Hart River	Zn,Cu,Ag,(Pb,Au)	.525	3.6	0.9	1.45	46	1.3	Wernecke Supergroup
2	NA	Purcell Basin	1A	Kootenay King	Zn,Pb,Ag	0.01	P 15.6	5.36		66.5		M. Aldridge slt,sh,sst
3	NA	Purcell Basin	1A	Sullivan	Pb,Zn,Ag,(Cd,Sn)	155		5.7	6.6	68		Purcell/Lower Aldridge
4	NA	Purcell Basin	1A	North Star	Pb,Zn,Ag	.061	P 6.12	35.5		673		Purcell/Lower Aldridge
5	NA	Purcell Basin	1A	Sternwinder	Zn,Pb,Ag	0.05	P 15.6	3.7		76.3		Purcell/Lower Aldridge

Deposit Types: 1A — clastic hosted SEDEX

P — tonnage as production only; other tonnage figures reserves plus production

TABLE 3-3

Cambrian-Middle Devonian Sedimentary Exhalative Deposits

Map No.	Terrane	Tectonic Element	Dep. Type	Deposit Name	Commodity	Million Tonnes	Zn %	Pb %	Cu %	Ag g/t	Au g/t	Host Rocks
Early Cambrian												
6	KO	Selkirk Allochthon	1B	Rift	Zn,Pb,(Cu)							Hamill or Lardeau?
7	KO	Shuswap Complex	1B	Kingfisher Creek	Zn,Ag,Pb,(Cu,F)							paragneiss
8	KO	Shuswap Complex	1B	Ruddock Creek	Zn,Pb,Ag,(F,Ba)	5	7.5	2.5				paragneiss
9	KO	Shuswap Complex	1B	CK	Pb,Zn,Ag,(Cu,Au)	.5-1	15	3				paragneiss
10	KO	Shuswap Complex	1B	Summit	Zn,Pb,Ag,Cu							paragneiss
11	MO	Monashee Complex	1B	Big Ledge	Zn	6.5	4					paragneiss
12	MO	Monashee Complex	1B	Jordan River	Zn,Pb,Ag,(Ba,F)	2.61	5.6	5.1		35		paragneiss
13	MO	Monashee Complex	1B	Cottonbelt	Pb,Zn,Ag	.8	2	6		50		paragneiss
14	KO	Kootenay Arc	1C	Duncan	Pb,Zn	2.76	3.1	3.3				Badshot limestone
15	KO	Kootenay Arc	1C	Jersey	Zn,Pb,Ag,(Cd);W	7.68 P	3.49	1.65		3.08		Reeves limestone
16	KO	Kootenay Arc	1C	HB	Zn,Pb,Ag,(Au)	6.45 P	4.1	.77		4.8	.002	Reeves limestone
17	KO	Kootenay Arc	1C	Reeves-MacDonald	Zn,Pb,Ag,(Cu,Cd, Ga,Ge)	5.8 P	3.42	0.98		3.4		Reeves limestone
18	KO	Kootenay Arc	1C	Wigwam	Zn,Pb,(Au,F)	8.48	3.54	2.14				Badshot limestone
19	KO	Kootenay Arc	1C	J & L	Zn,Pb,Ag(Au)	4.77	4.3	2.70		72	7.2	Hamill Group
20	KO	Kootenay Arc	1C	Mastodon	Zn,Pb,Ag	.029 P	9.25	0.28		6.56		Badshot limestone
21	KO	Adams Plateau	2	Mosquito King	Pb,Zn,Ag							Eagle Bay
22	KO	Adams Plateau	2	Lucky Coon	Pb,Zn,Ag							Eagle Bay
23	KO	Adams Plateau	2	Twin Mountain	Pb,Zn,Ag,(Cu,Au)							Eagle Bay
Cambrian-Ordovician												
24	CA	Cassiar Platform	1A	Sunset (Lower)	Pb,Zn,Ag							Kechika
25	CA	Cassiar Platform	1A	JA	Pb,Zn,Ag							Kechika
26	NA	Selwyn Basin	1A	Swim	Zn,Pb,Ag	4.3	4.7	3.8		42		Mt. Mye graph. phyllite
27	NA	Selwyn Basin	1A	Grum	Zn,Pb,Ag,(Cu, Ba)	30.8	4.9	3.1		49		Mt. Mye graph. phyllite
28	NA	Selwyn Basin	1A	Dy	Zn,Pb,Ag,Cu,Au, Ba	21.1	6.7	5.5	0.12	84	0.95	Mt. Mye graph. phyllite
29	NA	Selwyn Basin	1A	Vangorda	Zn,Pb,Ag,Au,(Cu, Ba)	7.1	4.3	3.4		48		Mt. Mye graph. phyllite
30	NA	Selwyn Basin	1A	Faro	Zn,Pb,Ag,(Cu,Ba)	57.6	4.7	3.4		36		Mt. Mye graph. phyllite
31	NA	Selwyn Basin	1A	SB	Cu,Zn							Mt. Mye graph. phyllite
32	NA	Selwyn Basin	1A	Sea	Cu,Zn							Mt. Mye graph. phyllite
33	NA	Selwyn Basin	1A	Mel	Zn,Pb,Ba	4.8	5.61	2.05				Kechika limestone, shale
34	KO	Selkirk Allochthon	2	Goldstream	Cu,Zn,Ag	3.175	3.123		4.49	20		Lardeau

Deposit Types: 1A — clastic hosted SEDEX; 1A1 — bedded barite; 1A2 — mainly feeder zone mineralization; 1B — clastic-carbonate hosted SEDEX; 2 — volcanic-sediment hosted; Terranes: NA — North America; KO — Kootenay; CA — Cassiar; MO — Monashee; P — tonnage based on production; other tonnage figures reserves plus production

TABLE 3-3

Cambrian-Middle Devonian Sedimentary Exhalative Deposits — Continued.

Map No.	Terrane	Tectonic Element	Dep. Type	Deposit Name	Commodity	Million Tonnes	Zn %	Pb %	Cu %	Ag g/t	Au g/t	Host Rocks
Middle Ordovician												
35	CA	Cassiar Platform	1A	JA (Upper)	Pb,Zn,Ag							Road River shale
36	NA	Kechika Trough	1A	Reb	Fe,(Zn)							Road River shale
37	NA	Kechika Trough	1A1	Aikie-Sika	Ba							Road River shale
Early Silurian												
38	NA	Selwyn Basin	1A	Maxi	Zn,Pb,(Ag)							Road River
39	NA	Kechika Trough	1B	CT	Ba,Zn,(Pb)							Road River Ist. dol.,chert
40	NA	Kechika Trough	1B	Ern	Zn,Ba							Road River Ist. dol.,chert
41	NA	Kechika Trough	1B1	Aikie-Sika	Ba							Road River Ist. dol.,chert
42	NA	Selwyn Basin	1B	Howard's Pass (XY)	Zn,Pb	125	5.4	2.1				Road River Ist. dol.,chert
43	NA	Selwyn Basin	1B	Grand (Nor)	Pb,Zn							Road River Ist. dol.,chert
44	NA	Selwyn Basin	1B	Anniv	Zn,Pb							Road River Ist. dol.,chert
Early-Middle Devonian												
45	CA	Cassiar Platform	1A	Angie	Zn,Ag							Road River shale
46	NA	Selwyn Basin	1B	Vulcan	Zn,Pb,Ba, (Ag, F, Cu)							Road River shale

Deposit Types: 1A — clastic hosted SEDEX; 1A1 — bedded barite; 1A2 — mainly feeder zone mineralization; 1B — clastic-carbonate hosted SEDEX; 2 — volcanic-sediment hosted; Terranes: NA — North America; KO — Kootenay; CA — Cassiar; MO — Monashee; P — tonnage based on production; other tonnage figures reserves plus production

The temporal and spatial distribution of sedimentary-exhalative deposits define major metallogenic epochs that were coeval with periods of rifting along the ancient continental margin of ancestral North America. These metallogenic events occurred during a long history of intracratonic and passive margin sedimentation that preceded accretion of volcanic arcs to the North American craton in Mesozoic and Cenozoic time (Thompson *et al.*, 1987). Recognition of the importance of this relationship is critical to mounting a successful exploration program for this class of mineral deposit.

The largest and most economically important deposits discovered to date are of Middle Proterozoic (Sullivan), Cambrian (Anvil district), Early Silurian (Howard's Pass district) and Late Devonian to Mississippian age (MacMillan Pass district, Gataga district, Red Dog). Minor events (in terms of deposits discovered to date) occurred during the Late Cambrian to Early Ordovician, Middle Ordovician and Early to Middle Devonian.

The most economically important sedex deposits are found in the Selwyn and Purcell basins where the main host rocks are starved-basin chemical sediments and distal turbidites. West of these basins, shallow water, mixed carbonate — clastic platform

sequences of the Cassiar Terrane and metamorphosed equivalents in the Kootenay Arc and Shuswap Metamorphic Complex host numerous, small statiform massive sulphide deposits that may also be considered part of the sedex group. Outboard or tectonically overlying the platform rocks are mixed metavolcanic-metasedimentary sequences of the Eagle Bay, Selkirk and Pelly Mountain assemblages which also contain important stratiform massive sulphide deposits that have both sedex and volcanogenic characteristics. These volcanic rich successions were probably deposited in marginal basins along a rifted continental margin or as part of a young volcanic arc.

The following sections will discuss sedimentary-exhalative deposits in terms of their age and tectono-stratigraphic setting. Type deposits will be described briefly. The reader is referred to the references cited for each deposit for a more complete description of individual deposits and districts. Much of the information presented in this paper has been derived from excellent overview papers by Höy (1982a), Came and Cathro (1982), Abbott *et al.* (1986) and Dawson *et al.* (in press).

In Tables 3-2, 3-3 and 3-4 the deposits have been grouped into three main categories. Group 1

includes the true sedimentary-exhalative deposits. Two subdivisions are used — one for deposits in fine-grained basinal sediments, mainly chert, siliceous shale and turbidites (1A) and another for deposits in mixed carbonate and clastic successions (1B). Group 2 includes deposits that are hosted by mixed volcanic and sedimentary sequences and could be classified as volcanogenic; group 3 includes the carbonate-hosted Mississippi Valley-type deposits. Groups 2 and 3 are discussed elsewhere in this vol-

ume and are only briefly mentioned here because of their close genetic link with sedimentary-exhalative deposits.

MIDDLE PROTEROZOIC

Some of the world's largest sedimentary-exhalative deposits occur in rocks of Middle Proterozoic age (Table 3-1). In the Canadian Cordillera, the most important deposit of this age is Sullivan, located in southeast British Columbia (Figure 3-4).

TABLE 3-4

Late Devonian to Mississippian Sedimentary Exhalative Deposits

Map No.	Terrane	Tectonic Element	Dep. Type	Deposit Name	Commodity	Million Tonnes	Zn %	Pb %	Cu %	Ag g/t	Au g/t	Host Rocks
Late Devonian — Mississippian												
47	NA	Kechika Trough	1A	Elf	Pb,Zn,Ag,Ba							Lower Earn ch. arg., shale
48	NA	Kechika Trough	1A	Fluke	Pb,Zn,Ag,Ba							Lower Earn ch. arg., shale
49	NA	Kechika Trough	1A	Pie	Pb,Zn,Ag,Ba							Lower Earn ch. arg., shale
50	NA	Kechika Trough	1A	Cirque	Zn,Pb,Ag,Ba	32.2	7.9	2.1		48		Lower Earn ch. arg., shale
51	NA	Kechika Trough	1A	Mount Alcock	Zn,Pb,Ag,Ba							Lower Earn ch. arg., shale
52	NA	Kechika Trough	1A	Bear	Pb,Zn,Ag,Ba		10	5.7		52		Lower Earn ch. arg., shale
53	NA	Kechika Trough	1A	Driftpile Creek	Pb,Zn,Ba							Lower Earn ch. arg., shale
54	NA	Kechika Trough	1A1	Kwadacha	Ba							Lower Earn ch. arg., shale
55	NA	Selwyn Basin	1A	Matt Berry	Pb,Zn,Ag,Sb	0.5	4.6	6.1		105		Lower Earn
56	NA	Selwyn Basin	1A	Fin	Pb,Zn,Ag							Lower Earn
57	NA	Selwyn Basin	1A	Tom (E & W)	Zn,Pb,Ag,Ba	15.7	7.0	4.6		49.1		Lower Earn
58	NA	Selwyn Basin	1A	Jason (Main,S,End)	Pb,Zn,Ag,Ba	15.5	6.6	7.1		79		Lower Earn
59	NA	Selwyn Basin	1A1	Oro	Ba							Lower Earn
60	NA	Selwyn Basin	1A1	Moose	Ba							Lower Earn
61	NA	Selwyn Basin	1A1	Cathy	Ba							Lower Earn
62	NA	Selwyn Basin	1A2	Nidd	Zn,(Pb)							Lower Earn
63	CA	Cassiar Platform	2	Clear Lake	Zn,Pb,Ag,(Ba)							Lower Earn
64	KO	Adams Plateau	2	Homestake	Ag,Zn,Pb,Cu, Ba,(Au)	1.01	4	2.5	0.6	248	0.68	Eagle Bay metavolc., phyl.
65	KO	Adams Plateau	2	Rea	Zn,Pb,Cu,Ag, Au	0.24	2.3	2.1	0.5	75	6.8	Eagle Bay metavolc., phyl.
Mississippian												
66	CA	Cassiar Platform	1A	GK, Dirck	Ba							Upper Earn turbidites
67	CA	Cassiar Platform	2	MM	Pb,Zn,Ag							Upper Earn shale, volc.
68	NA	Selwyn Basin	1A1	Tea	Ba							Upper Earn turbidites
69	NA	Selwyn Basin	2	Marg		1.92	5.19	2.72	1.97	67	1.02	Upper Earn shale, volc.

Deposit Types: 1A — clastic hosted SEDEX; 1A1 — bedded barite; 1A2 — mainly feeder zone mineralization; 1B — clastic-carbonate hosted SEDEX; 2 — volcanic-sediment hosted; Terranes: NA — North America; KO — Kootenay; CA — Cassiar; MO — Monashee; Tonnages reserves plus production

SEDEX DEPOSITS OF THE CANADIAN CORDILLERA

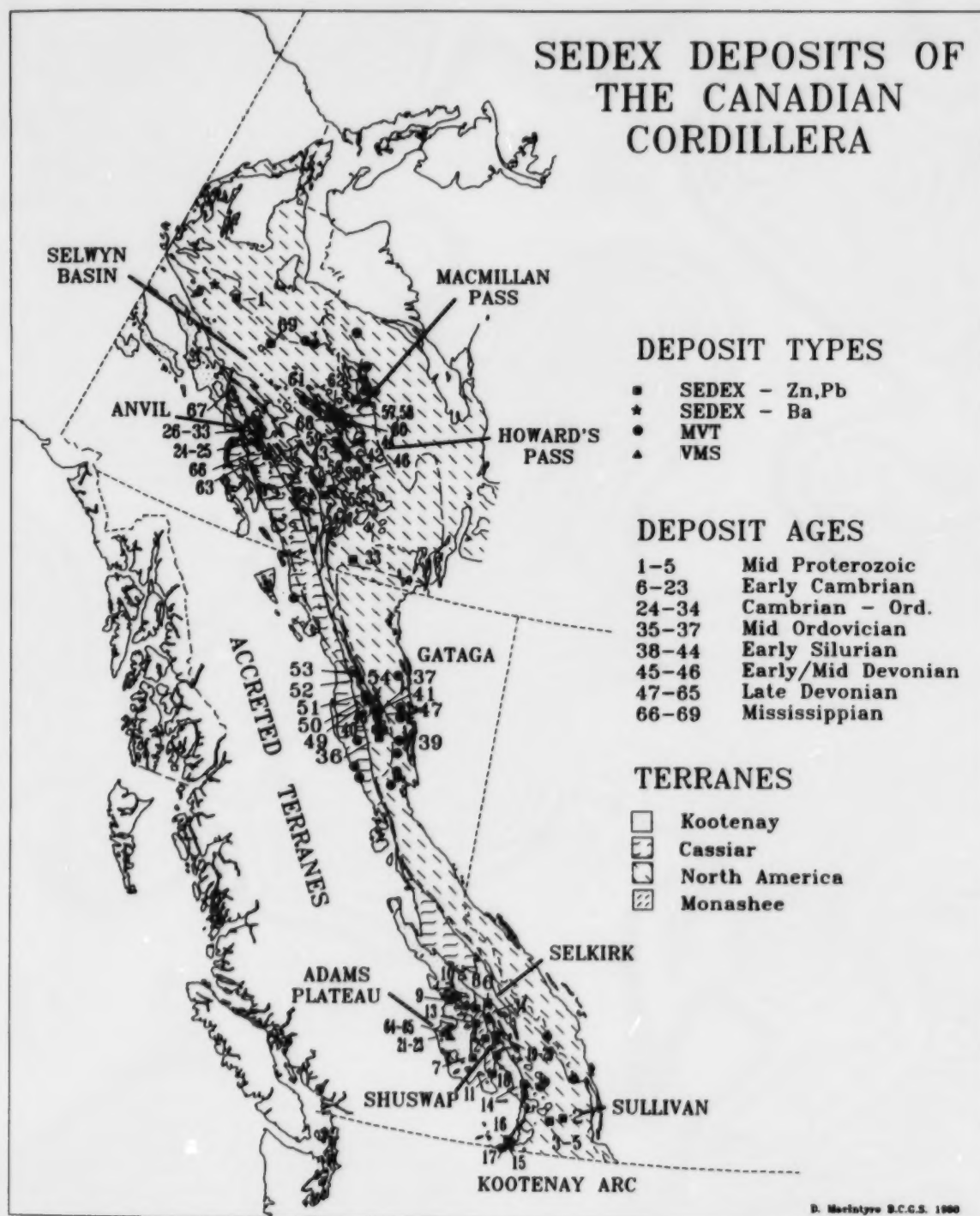


Figure 3-2. Location of sedimentary exhalative deposits in the Canadian Cordillera. Numbers refer to deposits listed in tables 3-2, 3-3 and 3-4.

Figure 3-3. Restored stratigraphic section across the Cordilleran miogeoclinal in Yukon and Northwest Territories. From Abbott et al., 1986.

Sullivan District

Continently-derived turbidites were deposited along the margin of ancestral North America during Middle Proterozoic time. In southeastern British Columbia up to 11 kilometres of clastic and carbonate sediment of the Purcell Supergroup accumulated in a northerly-trending intracratonic or passive continental margin basin (Höy, 1989; Figures 3-5 and 3-6). Rapid facies changes, turbidite deposition, local sedimentary thickening and the accumulation of intraformational conglomerates within the Purcell Supergroup are cited as evidence for synsedimentary faulting during Middle Proterozoic time (Kanase-wich, 1968; Höy, 1982a). The world class Sullivan deposit, and the much smaller North Star, Kootenay King and Stenwinder deposits (Figure 3-4; Table 3-2) also formed at this time. These deposits are hosted by fine to coarse turbidites and fault-related intraformational conglomerates near the top of the lower Aldridge Formation. Zones of tourmaline alteration and sulphide accumulation may have been localized along a series of northeast-trending faults that were active during Middle Proterozoic time (Figure 3-4).

The Sullivan mine ranks as one of the world's largest base metal producers. Hamilton *et al.* (1983) and Campbell *et al.*, 1978, 1980 have published extensive descriptions of the orebody and Höy (1982a) has discussed its regional tectonic and stratigraphic setting. The deposit is over 2000 metres in diameter and is up to 100 metres thick (Figures 3-7 and 3-8). The core of the orebody includes a lens of pyrrhotite-rich massive sulphide that grades upward and laterally eastward into laminated pyrrhotite-sphalerite-galena (Plate 3-1). Massive beds of finely laminated sulphide interbedded with wacke comprise a distal ore facies. A distinctive feature of the Sullivan deposit is a well-developed breccia zone that cuts footwall intraformational conglomerate, siltstone and wacke. Extensive veining and tourmaline, albite, chlorite and carbonate alteration are spatially associated with the breccia. Extensive albite alteration occurs in the hangingwall and is clearly post ore (Hamilton *et al.*, 1983).

An important feature of the Sullivan camp is the presence of synsedimentary diorite sills and dikes within the Aldridge Formation. These intrusions were emplaced prior to complete lithification of the host sediments and therefore, a U-Pb age date of 1445 Ma obtained from a coarse-grained sill dates both the Aldridge sediments and the Sullivan deposit (Höy, 1989). This age is very close to the 1430 Ma age obtained by LeCouteur (1979) for the Sullivan deposit. The compositional trends of the sills support a model for deposition of the Aldridge Formation in a subsiding intracratonic basin formed by Middle Proterozoic rifting (Höy, 1989).

Other Deposits

Sedimentary-exhalative deposits also occur in dolomitic to argillaceous siltstones of the Middle



Plate 3-1. Deformed and laminated sulphides from the Sullivan deposit southeastern British Columbia.

Aldridge formation. The most important of these is the small Kootenay King deposit located east of the Rocky Mountain Trench (Höy, 1982a).

In addition to stratiform zinc-lead deposits, Middle Proterozoic shallow water quartz arenites and related red beds host stratabound copper-silver mineralization, for example the Spar Lake deposit. Similar widespread stratabound copper-silver mineralization also occurs at the same stratigraphic horizon in the Lewis thrust sheet in southeastern British Columbia (Morton *et al.* 1973). These deposits may also be related to Middle Proterozoic rifting and related hydrothermal activity (Dawson *et al.*, in press).

Wernecke Supergroup

Although Middle Proterozoic basinal-facies turbidites occur in the Wernecke and Ogilvie Mountains of the northern Yukon Territory, the only deposit discovered to date is the Hart River deposit (Abbott, 1987). This zinc-copper massive sulphide deposit, which is hosted by black argillites that underlie basaltic pillow lavas, occurs near the top of the Wernecke Supergroup (Abbott, 1987). It has been dated at 1240 to 1280 Ma (Morin, 1978) and is therefore younger than the Sullivan deposit.

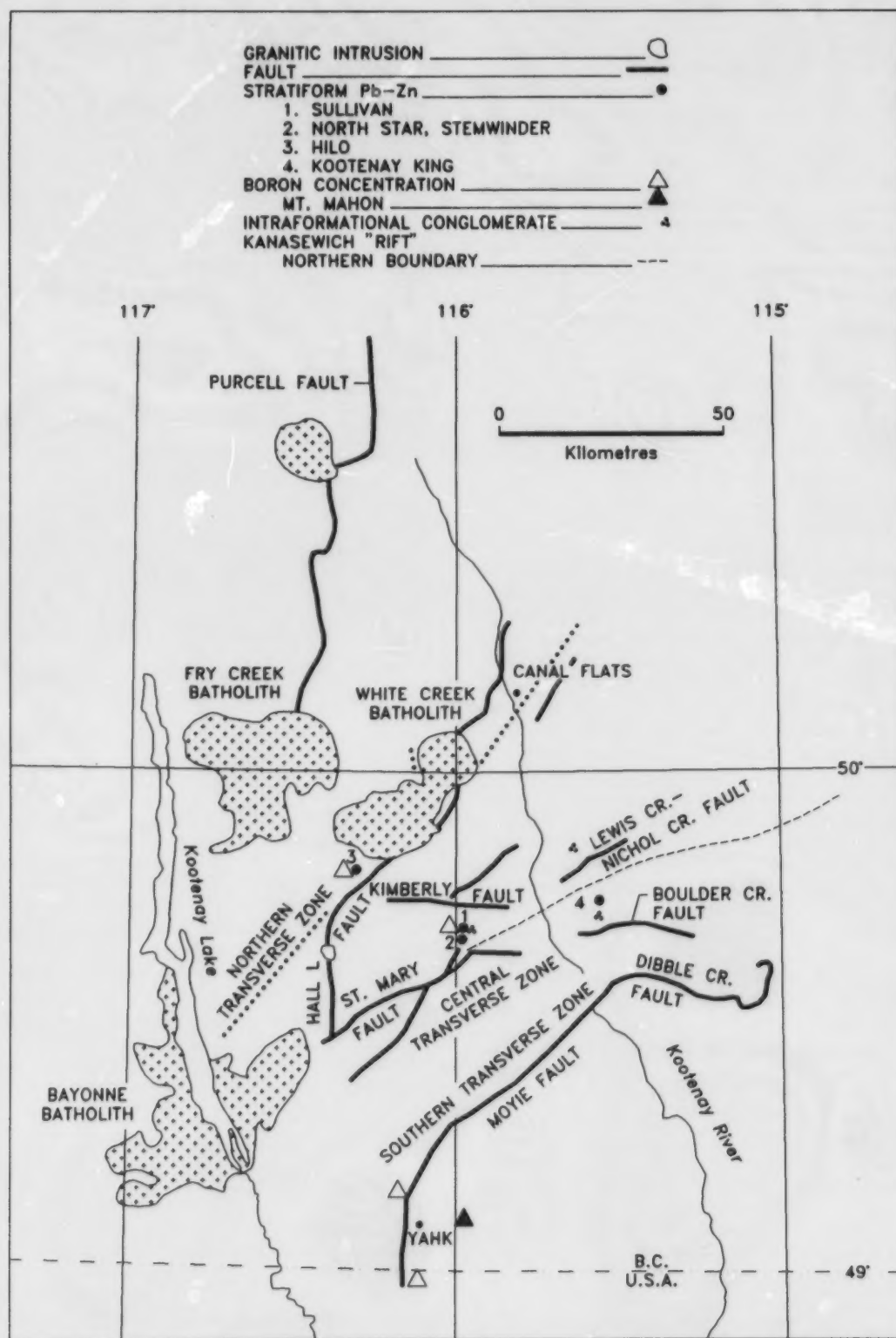


Figure 3-4. Location of faults, boron concentrations and intraformational conglomerate relative to Middle Proterozoic Pb-Zn deposits, southeast B.C. From Höy, 1982.

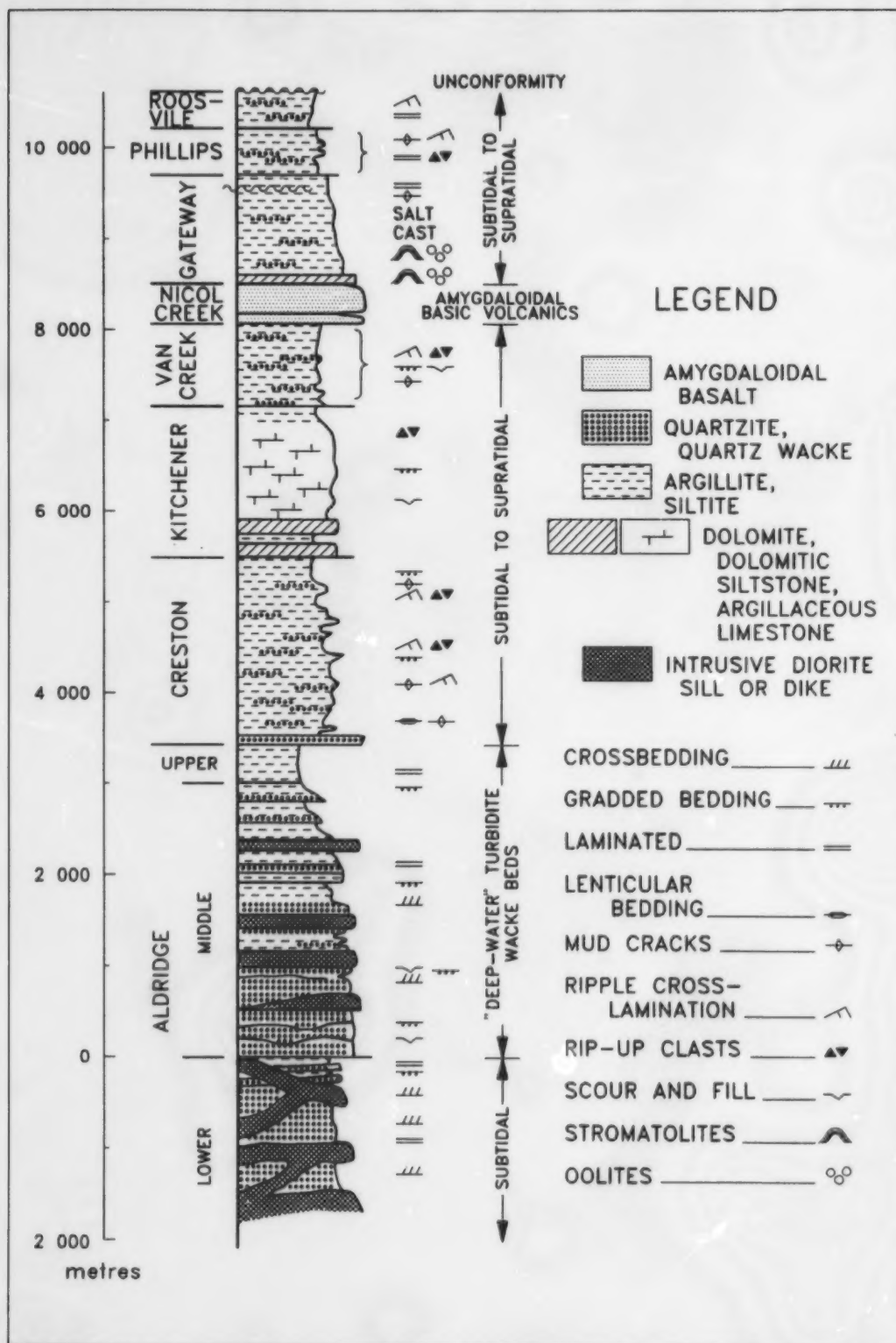


Figure 3-5. Composite stratigraphic column of the Purcell Supergroup in the Moyie Lake area. From Høy, 1982.

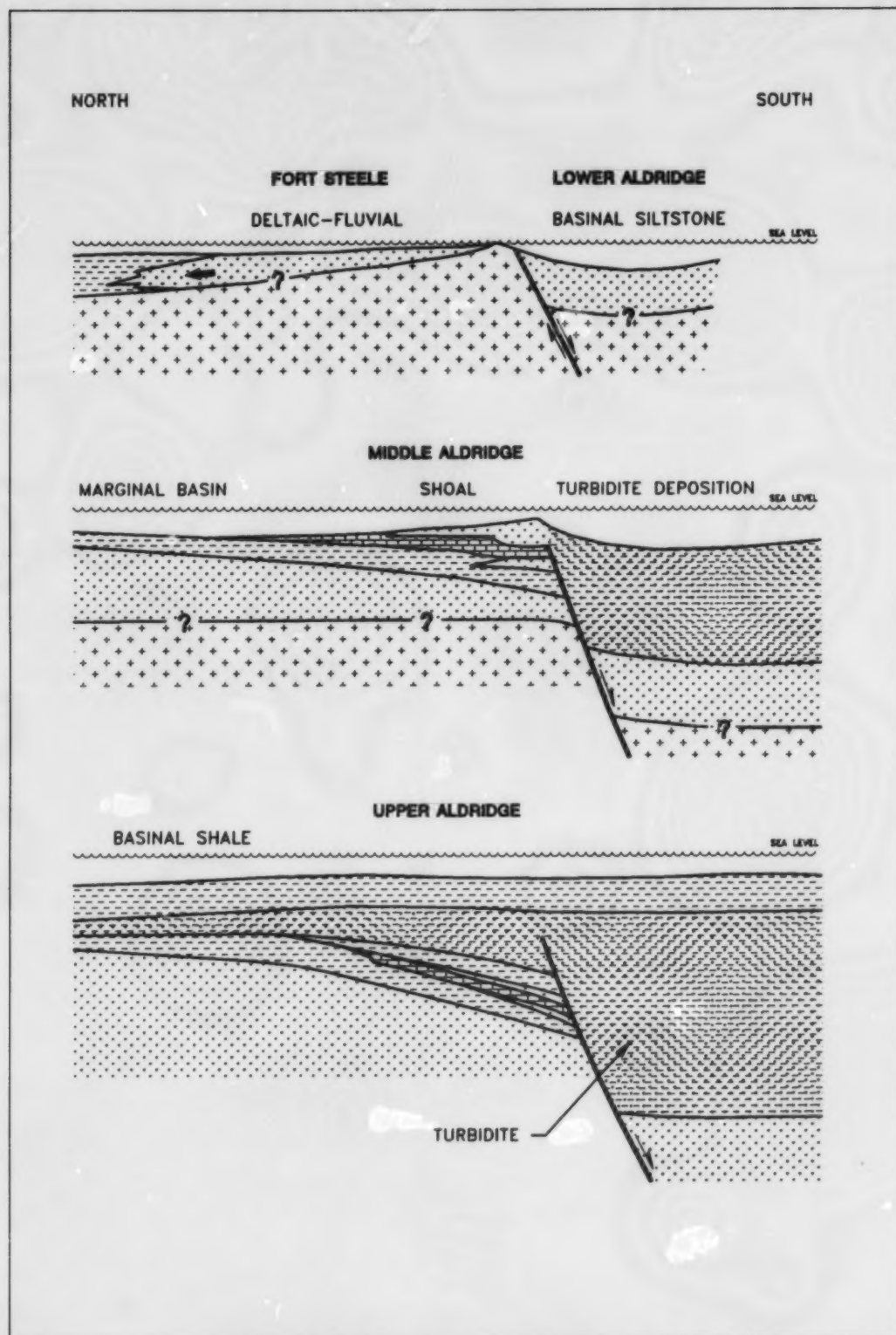


Figure 3-6. Postulated stages in the evolution of the marginal Kootenay King basin and a fault bounded deep water turbidite basin to the south during Aldridge time. From Höy, 1982a.

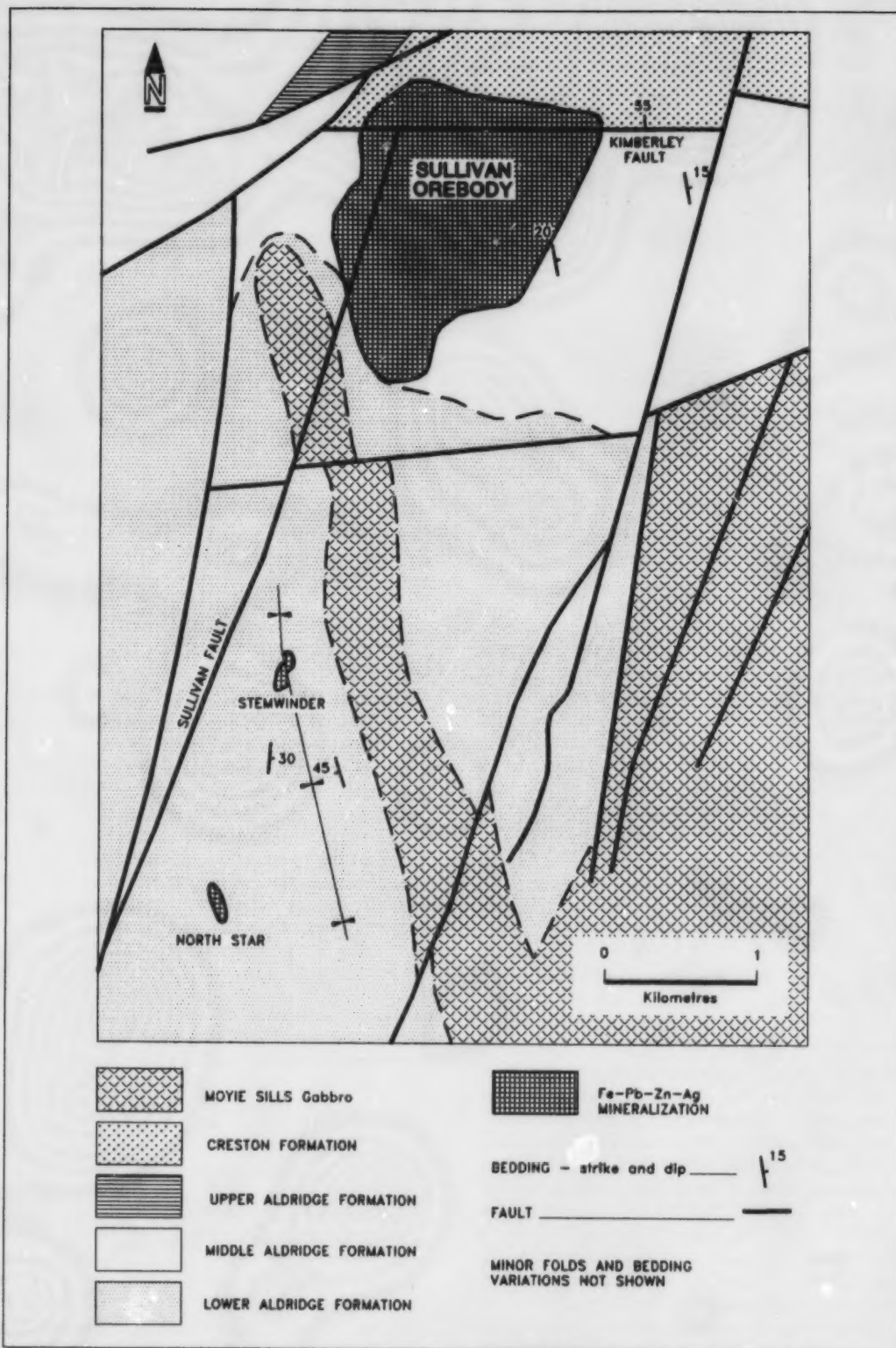


Figure 3-7. Local geology of the Sullivan orebody. The surface projection of the orebody is shown.
From McClay, 1983.

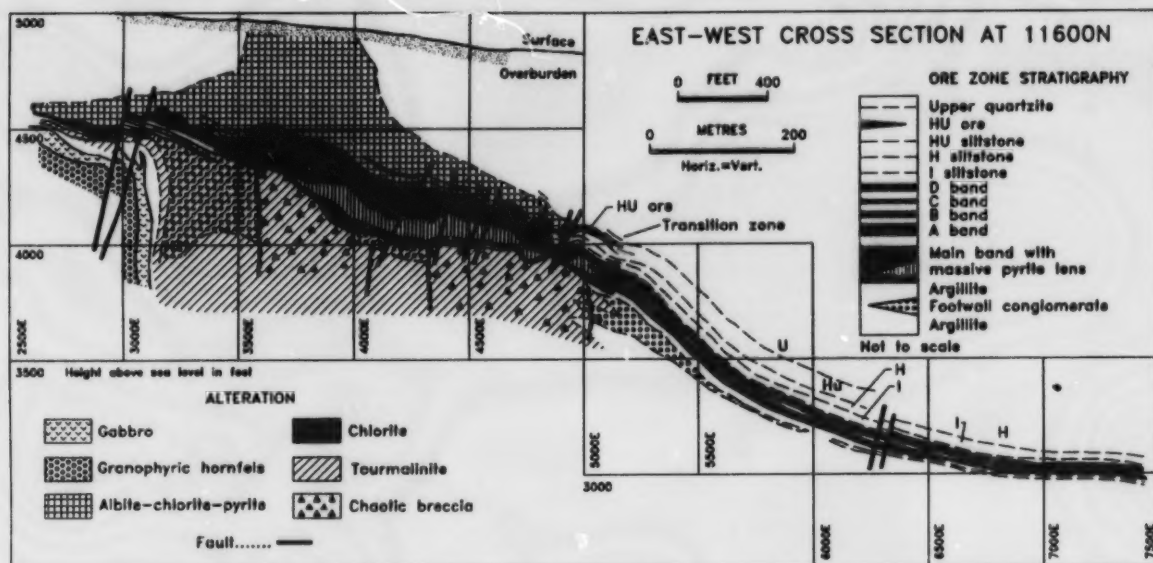


Figure 3-8. Cross section of the Sullivan orebody. From McClay, 1983.

Muskwa Assemblage

In northeast British Columbia, a Middle Proterozoic platformal succession is exposed in the Muskwa Ranges. No stratiform lead-zinc deposits have been discovered in these rocks but northeast-trending chalcopyrite-pyrite-quartz-ankerite veins of the Churchill Copper camp are believed to be Middle Proterozoic in age (Preto and Tidsbury, 1971; Carr, 1971). These veins, which are cut by post mineral diabase dikes, occur in basinal clastic and impure carbonate rocks of the Aida and Gataga formations. The copper-rich veins could be localized along northeast-trending syndimentary faults and if so the host sedimentary strata might contain stratiform massive sulphide deposits. The localization of diabase dikes along the same faults is a favourable indication that rifting was deep-seated and was accompanied by high-heat flow.

Mackenzie Mountains Supergroup

The Mackenzie Mountains Supergroup is a shallow-water platformal succession that was deposited during the late Middle Proterozoic, prior to Windermere sedimentation. Dolostone of the lower Little Dal Group hosts the numerous Mississippi Valley type lead-zinc deposits of the Gayna River camp. Widespread syndimentary faulting and development of linear reef structures is cited as evidence for a syn-mineralization rifting event (Eisbacher, 1981). Such a rifting event might have resulted in formation of stratiform lead-zinc deposits in time equivalent basinal-facies strata although none have been found to date. The spatial and temporal association of carbonate-hosted and clastic-hosted mineral districts is evident in Figure 3-2, particularly for the

Devonian deposits. This relationship may also hold true for the older Proterozoic deposits.

LATE PROTEROZOIC

The Late Proterozoic was a time of extensive clastic sedimentation along the edge of the North American continental landmass. These thick clastic deposits record a history of repeated rifting of the continental margin and a clear westward deepening polarity as the Cordilleran miogeocline became firmly established. A major rifting event is recorded by a number of intrusive and extrusive units that give isotopic ages around 770 Ma. Surprisingly, the only sulphide deposits that can be related to this event are disseminated copper, iron and minor lead and zinc sulphides in sabkha-type algal limestone beds (Jefferson and Ruell, 1986). However, stratiform mineralization in the form of hematite-jaspilite iron formation is hosted by siltstone and mixite of the Rapitan Group. The Crest iron deposit contains over 5.6 billion tonnes of iron formation averaging 47.2 per cent iron (Stuart, 1963; Dawson *et al.*, in press). Gross (1965) proposed that the hematite and silica were deposited as a chemical sediment from fumarolic waters discharged into a marine basin along syndimentary faults. This same marine basin, which contains rift-related mafic volcanic rocks, may also be good hunting ground for sedimentary-exhalative deposits.

CAMBRIAN TO MIDDLE DEVONIAN

From Early Cambrian to Middle Devonian time the continental margin of ancestral North America was comprised of a series of rift-controlled basins that may or may not have been open to the sea. The

largest of these was the Selwyn Basin in the Yukon Territory and its southeastern extension, the Kechika trough (Figure 3-9). During this period of passive margin sedimentation a well-established, westward-thickening carbonate platform (Mackenzie platform in Yukon; MacDonald platform; in northeast British Columbia) developed along the rifted margin of the continental landmass. A restored stratigraphic section across the miogeocline is shown in Figure 3-3.

Platformal rocks of Cambrian to Middle Devonian age are also found in the Cassiar Terrane, which is in fault contact with rocks of the North American miogeocline from east-central British Columbia to central Yukon Territory. These rocks are similar to those of the inner miogeocline of ancestral North America and contain similar types of pre-accretion mineral deposits. The Cassiar Terrane is a fragment of the continental margin that has been moved 500 to 1000 kilometres northward along the Tintina and Northern Rocky Mountain Trench fault systems in Late Mesozoic to early Tertiary time (Gabrielse, 1984; Gabrielse and Yorath, in press).

Similar basins apparently existed in southeastern British Columbia but the intensity of deformation and crustal shortening within the Kootenay Terrane has made delineation of these basins and stratigraphic correlations difficult. High grade metamorphic core complexes have further modified the Early to Middle Paleozoic basinal and platformal successions.

EARLY CAMBRIAN

A major metallogenic event is associated with Early to Middle Cambrian rifting of the continental margin. This rifting resulted in a series of linear uplifts that were capped by platformal sedimentary rocks. In the Kootenay and Monashee terranes, shallow water carbonates and interbedded clastic rocks host the important stratiform zinc-lead deposits of the Kootenay Arc, Shuswap and Adams Plateau camps. In the northern Cordillera, basinal-facies graphitic phyllites of probable Cambrian age host the large-tonnage stratiform deposits of the Anvil camp and Mississippi Valley-type deposits occur in Early Cambrian Atan limestone of the Cassiar platform (Ingenika camp).

Kootenay Arc Deposits

The Kootenay Arc is an arcuate belt of complexly deformed sedimentary, volcanic and metamorphic rocks. Within it, an Early Cambrian succession of shallow marine carbonate, quartzite, and schist hosts several stratiform sulphide deposits (Sangster, 1986; Höy, 1982a). The deposits are comprised of conformable and crosscutting masses of pyrite, sphalerite and galena in dolomite or silica-altered, strongly deformed limestone of the Badshot or Reeves formation (Fyles, 1970). The largest and best known of this group of deposits is the Reeves-MacDonald; other important deposits include the Duncan, HB, Jersey, Jackpot, Mastodon and Wigwam (Table

3-3). These deposits have similar host rocks and paleotectonic setting to stratiform lead-zinc deposits of Ireland.

Shuswap Deposits

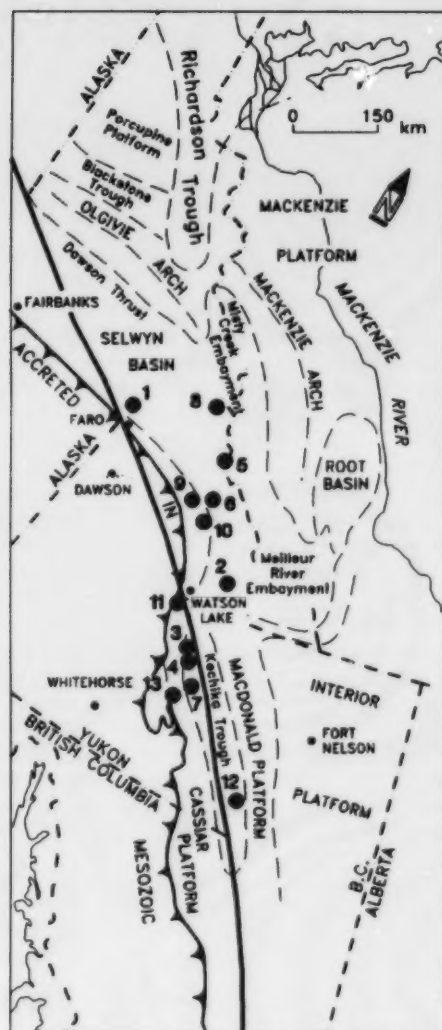
Sedimentary-exhalative massive sulphide deposits also occur in intensely metamorphosed and deformed platformal rocks of the Monashee and Shuswap metamorphic complexes east of the Kootenay Arc. The Monashee complex consists of core gneisses dated at 2800 and 2200 Ma that have been intruded by plutons dated at 2100 and 1960 Ma, respectively. These rocks are believed to represent basement to the North American plate. The core gneisses are overlain by paragneisses that are cut by syenite intrusions dated at 750 or 770 Ma (Okulitch, 1985).

The upper paragneiss succession, which unconformably overlies core paragneiss and orthogneiss, includes a platformal sequence of calcsilicate gneiss, marble, quartzite and pelitic schist that hosts the Cottonbelt, Jordan River, and Big Ledge deposits (Figure 3-10). Lead isotope ratios from these deposits plot in the Cambrian field of the shale growth curve of Godwin and Sinclair (1982) suggesting the deposits and their host rocks are Cambrian in age (Höy and Godwin, 1988). If this is true, then these deposits may be correlative with the less metamorphosed platformal deposits of the Kootenay Arc to the east. This would also imply that the platformal rocks and their contained mineral deposits were deposited on a basement high outboard from the Purcell and Windermere basins.

The Ruddock Creek, Kingfisher (Colby), CK and Summit deposits (Höy, 1975) occur in metasedimentary platformal rocks of the Shuswap Metamorphic Complex, a subdivision of the Kootenay Terrane. These deposits have similar mineralogy and hostrocks to those within the Monashee complex and are believed to be the same age. The deposits collectively define the Shuswap district (Table 3-3). The stratigraphic and structural setting of these deposits has been described by Höy (1987).

Because the Shuswap deposits have been intensely deformed and metamorphosed it is difficult to identify structural or stratigraphic features that may have controlled their formation. However, extrusive carbonatite layers do occur within the host succession for the Cottonbelt deposit (Höy and Kwong, 1986; Höy, 1987) implying deep-seated rifting accompanied exhalative activity.

The Shuswap deposits are characterized by thin, regionally extensive layers of massive to irregularly banded sulphides or a series of discontinuous lenses generally within a well-layered platformal succession of calcareous schist, marble and quartzite (Figure 3-11). Sulphide minerals include sphalerite and pyrrhotite with minor galena and pyrite. The Cottonbelt deposit also contains significant magnetite; barite and fluorite are present at the Jordan River deposit.



- 1 _____ ANVIL DISTRICT
- 2 _____ MEL DEPOSIT
- 3 _____ JA OCCURRENCE
- 4 _____ SUNSET OCCURRENCE
- 5 _____ HOWARD PASS DISTRICT
- 6 _____ MAXI OCCURRENCE
- 7 _____ ANGIE OCCURRENCE
- 8 _____ MacMILLIAN PASS DISTRICT
- 9 _____ FIN OCCURRENCE
- 10 _____ MATT BERRY OCCURRENCE
- 11 _____ CLEAR LAKE DEPOSIT
- 12 _____ GATAGA DISTRICT
- 13 _____ MM DEPOSIT, BNOB,
CHZERPNOUGH OCCURRENCE

Adams Plateau

The western margin of the Kootenay Terrane is characterized by a series of west-verging thrust sheets that include metasedimentary and meta-volcanic rocks of the Early to Middle Paleozoic Eagle Bay assemblage (Schiari and Preto, 1987). In the Adams Plateau area, metamorphosed phyllite, siltstone, quartzite, limestone and metavolcanic rocks of probable Cambrian age host several stratiform zinc-lead deposits, the most important of which are the Lucky Coon and Mosquito King. The presence of a significant volcanic component in the host stratigraphic succession distinguishes this district from most others in the Canadian Cordillera. The volcanic rocks are probably related to rifting along the outer edge of the continental margin.

Sedimentary-exhalative deposits of the Adams Plateau area are the most outboard examples of this class of deposit found in North American cratonic rocks. They are transitional into the volcanogenic class of massive sulphide deposits. Similar deposits occur in the Pelly Mountains of the Cassiar Terrane and may also be found in correlative rocks of the Barkerville and Nisutlin subterrains of central and northern British Columbia and Yukon.

Selkirk Mountains

The Selkirk "allochthon", a subdivision of the Kootenay Terrane is separated from the Shuswap and Monashee metamorphic complexes by the Columbia River fault zone. This terrane includes intensely deformed pelitic and calcareous schists, quartzite, limestone, dolostone, marble and meta-volcanic rocks that may be correlative with the Cambrian to Ordovician Lardeau Group. These rocks host stratiform massive sulphide deposits such as the arsenic-gold rich J & L and Rift (Meyers and Hubner, 1990; Höy, 1985). The copper-rich Goldstream deposit, which is hosted by a mixed metavolcanic-metasedimentary succession, may also be part of this metallogenic event. Stratigraphically, the deposits lie above a persistent limestone member that has been correlated with the Early Cambrian Badshot Formation, host to the Kootenay Arc zinc-lead deposits. The sedimentary succession is part of the Early Paleozoic miogeocline.

The presence of mafic volcanic members within the basinal sedimentary succession of the Cambro-Ordovician Lardeau group suggests rifting was contemporaneous with sedimentation. The sedimentary-exhalative deposits are most likely related to this rifting event.

Figure 3-9. Location of sedimentary exhalative deposits and configuration of tectonic elements after 450 kilometres of right lateral strike slip motion on Tintina Fault has been restored. Note displacement of B.C.-Yukon border. From Abbott et al., 1986. See also Figure 3-17.

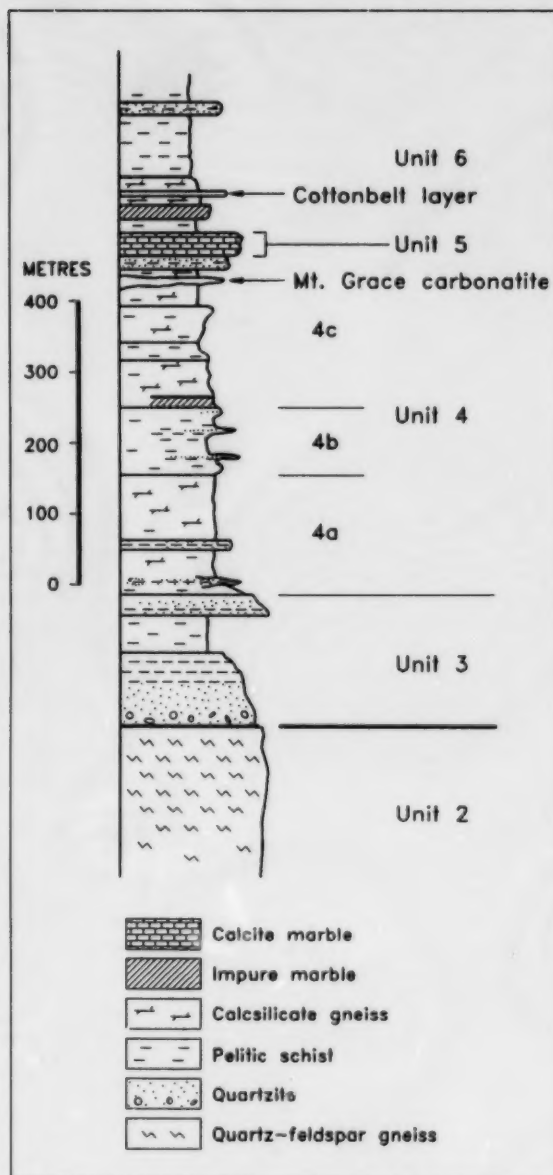
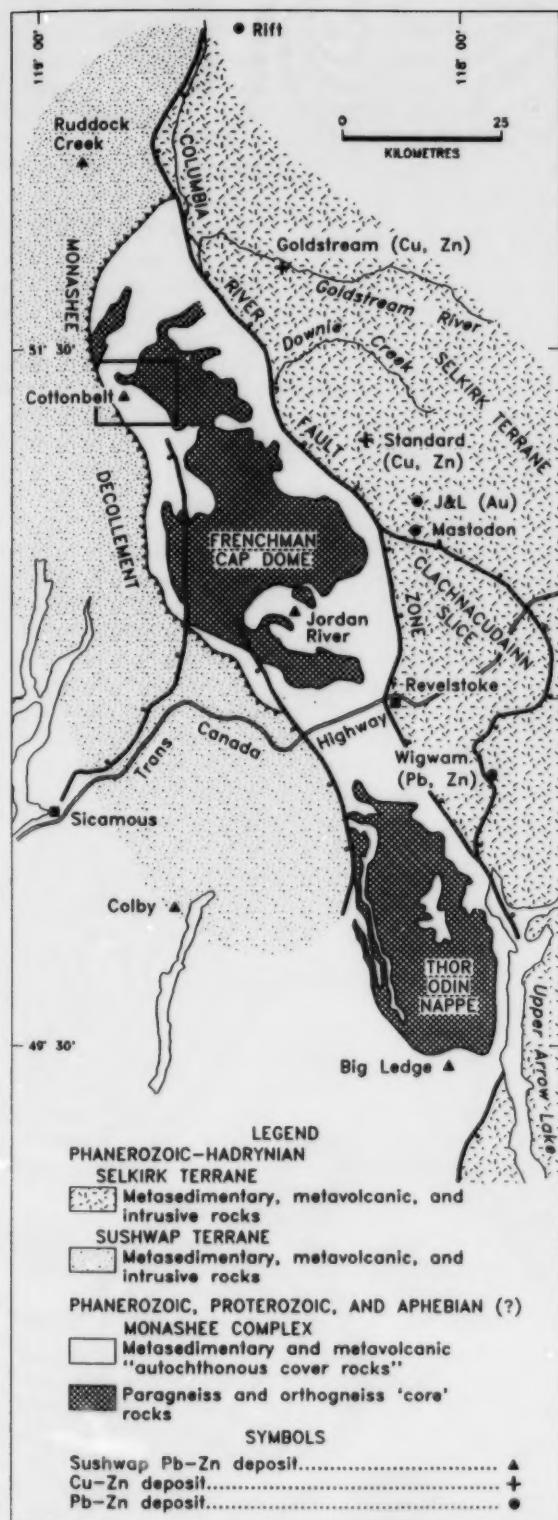


Figure 3-11. Stratigraphic position of Cottonbelt massive sulphide layer. From Höy and Godwin, 1988.

Figure 3-10. Tectonic map of the eastern margin of the Shuswap Complex and Selkirk Terrane, southeastern B.C. showing location of sedex mineral deposits. From Höy and Godwin, 1988.

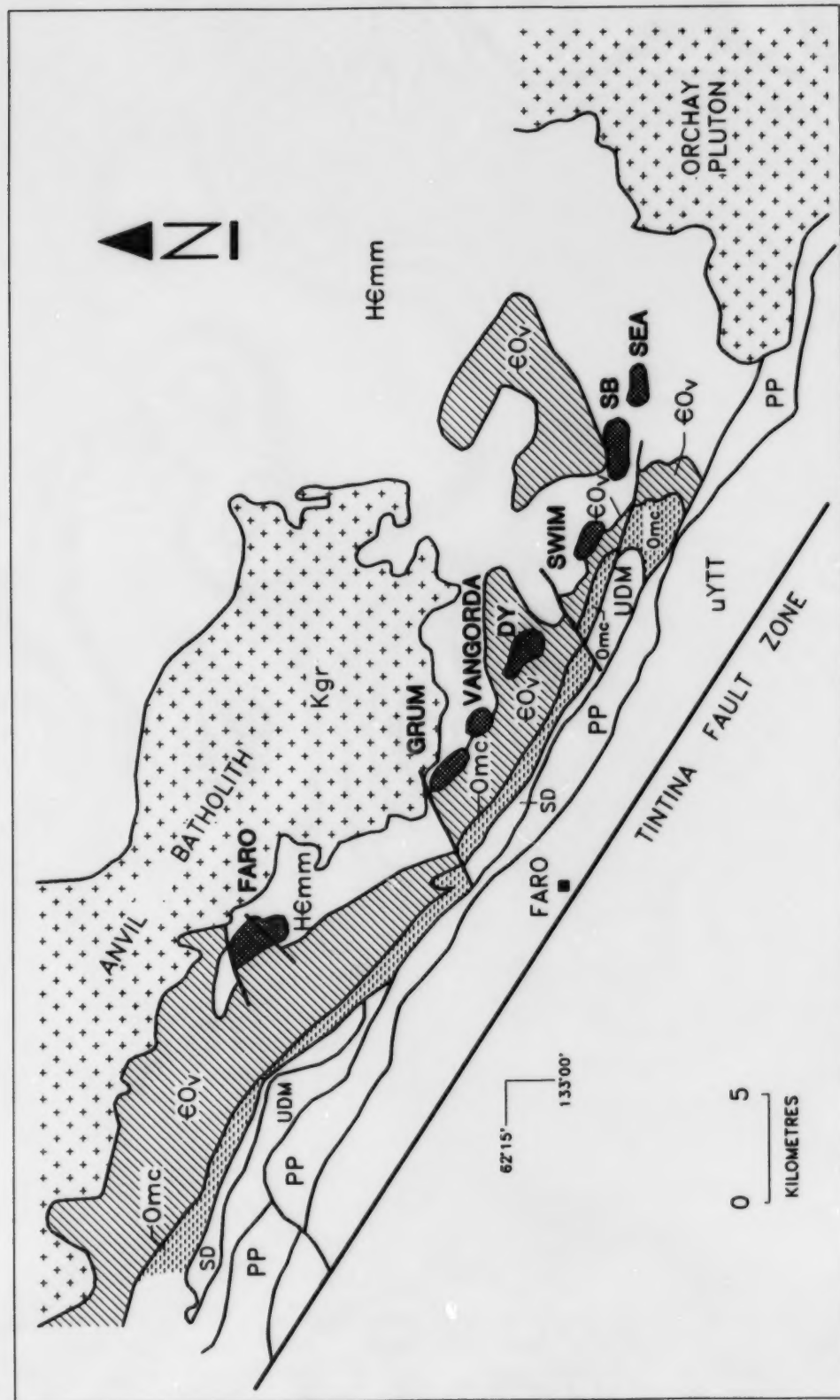


Figure 3-12. Geology of the Anvil District showing location of sedimentary-exhalative deposits (black); HEmm — Hachynian to Cambrian Mount Mye Fm.; COu — Cambrian to Ordovician Vangorda Fm.; Omc — Ordovician Menzies Creek volcanics; SD — Silurian-Devonian sediments; UDM — Devonian-Mississippian Earm Group; PP — Pennsylvanian-Permian Anvil Range Group; uYTT — Yukon-Tanana metasediments, Kgr — Cretaceous granitic intrusion. From Jennings and Jilson, 1986.

A major Cambrian sedimentary-exhalative mineral district also occurs in the northern Canadian Cordillera. Here, along the western margin of the Selwyn basin a thick succession of basinal-facies metasedimentary rocks hosts stratiform massive sulphide deposits of the Anvil camp.

Anvil Camp

The Anvil camp includes five stratiform pyritic zinc-lead-silver deposits — Faro, Grum, DY, Swim and Vangorda and two small pyritic copper-zinc deposits — Sea and SB (Figure 3-12). Jennings and Jilson (1986) have described the geologic setting and morphology of these deposits.

Deposits of the Anvil district occur within a belt of Early Paleozoic phyllites that is bounded by the Tintina fault to the southwest and the Cretaceous Anvil batholith to the northeast. Emplacement of the batholith and proximity to the fault zone have resulted in a complex pattern of metamorphism and deformation, making recognition of primary structural and stratigraphic features difficult.

Distinctive graphitic black phyllite or metapelite near the top of the Mount Mye Formation is the host stratigraphic unit for deposits of the district. Jennings and Jilson (1986) correlate these rocks with Early Cambrian rocks of eastern Selwyn Basin.

The Mount Mye Formation is overlain by calcareous and non-calcareous phyllites of the Vangorda Formation. These rocks have been correlated with calcareous phyllites and silty limestones of the Cambro-Ordovician Rabbitkettle Formation of the Selwyn Basin and the Kechika Group of northern British Columbia. Higher in the stratigraphic succession submarine volcanic rocks of the Menzie Creek formation are interfingering with graptolitic black shales of the Ordovician Road River Group.

Deposits of the Anvil district have a characteristic vertical zoning pattern called the "Anvil Cycle". This cycle includes a basal ribbon-banded graphitic quartzite that is successively overlain by pyritic quartzite, pyritic massive sulphide and baritic massive sulphide (Figure 3-13). A characteristic of some of the deposits is a white mica alteration zone which is best developed in the footwall. Some chalcopyrite-pyrrhotite stringer zones have also been recognized. Longitudinal and cross sections through the Faro deposit are shown in Figures 3-14a and 3-14b.

The deposits of the Anvil district are enriched in copper, and in some cases gold, relative to other Selwyn Basin sedimentary-exhalative deposits. Two deposits, the SB and Sea, are copper-zinc rich, suggesting a higher temperature of formation.

Other Cambrian Deposits

Although Cambrian basinal-facies clastic rocks are widespread within Selwyn Basin and the Kechika trough, the only other significant deposit of this age

is the Mel (Miller and Wright, 1986), a bedded barite-sulphide lens at the top of a Cambrian limestone sequence. Calcareous phyllites stratigraphically overlie the deposit and are correlated with the Cambrian to Ordovician Kechika Group.

The JA and Sunset deposits are hosted by an off-shelf clastic facies that is found along the northern margin of the Cassiar platform, southwest of the Tintina fault. Here, well-defined, laterally persistent laminations and bands of coarse-grained sphalerite, quartz, minor galena and carbonate occur in a hornfelsed calcareous siltstone that is near the top of the Kechika Group (Abbott *et al.*, 1986).

MIDDLE ORDOVICIAN (ROAD RIVER)

A major marine transgression occurred in Middle to Late Ordovician time, perhaps in response to crustal extension and basinal subsidence. During this period, black graptolitic mudstone and chert of the Road River Group was deposited throughout Selwyn Basin and the Kechika trough. Mafic submarine volcanic rocks were extruded during the early stages of this marine transgression particularly along the eastern margin of the shale basin. These volcanics were probably erupted along major rifts within and bounding the basin. In spite of a favourable tectonic and heat flow regime, the only known deposits of this age are the Reb and Aikie-Sika of the Gataga district (MacIntyre, 1983).

Gataga District

The Reb deposit is a massive pyrite lens with low zinc and lead values that is hosted by cherty black argillite of the Road River Group. These rocks are lithologically similar to those containing Middle Ordovician graptolites elsewhere in the district.

The Aikie-Sika showing is a laterally extensive barren barite bed, up to one metre thick, that occurs at the contact between quartz wacke turbidites and overlying late Middle Ordovician graptolitic black shales. The deposit formed close to the rift-controlled basin-platform transition zone along the eastern margin of the Kechika trough, in approximately the same stratigraphic interval as a belt of submarine volcanics further to the west. Barite also occurs in overlying Early Silurian rocks suggesting a multiple history of exhalative activity in this part of the Kechika trough.

EARLY SILURIAN

The Early Silurian was a time of shallow-water, starved-basin sedimentation within the Selwyn Basin and Kechika trough. During this time, the laterally extensive sulphide deposits of the Howard's Pass and Gataga districts were formed. By contrast to other metallogenic epochs, evidence for coeval tectonic activity is lacking in Early Silurian rocks. The Howard's Pass deposits appear to have formed by

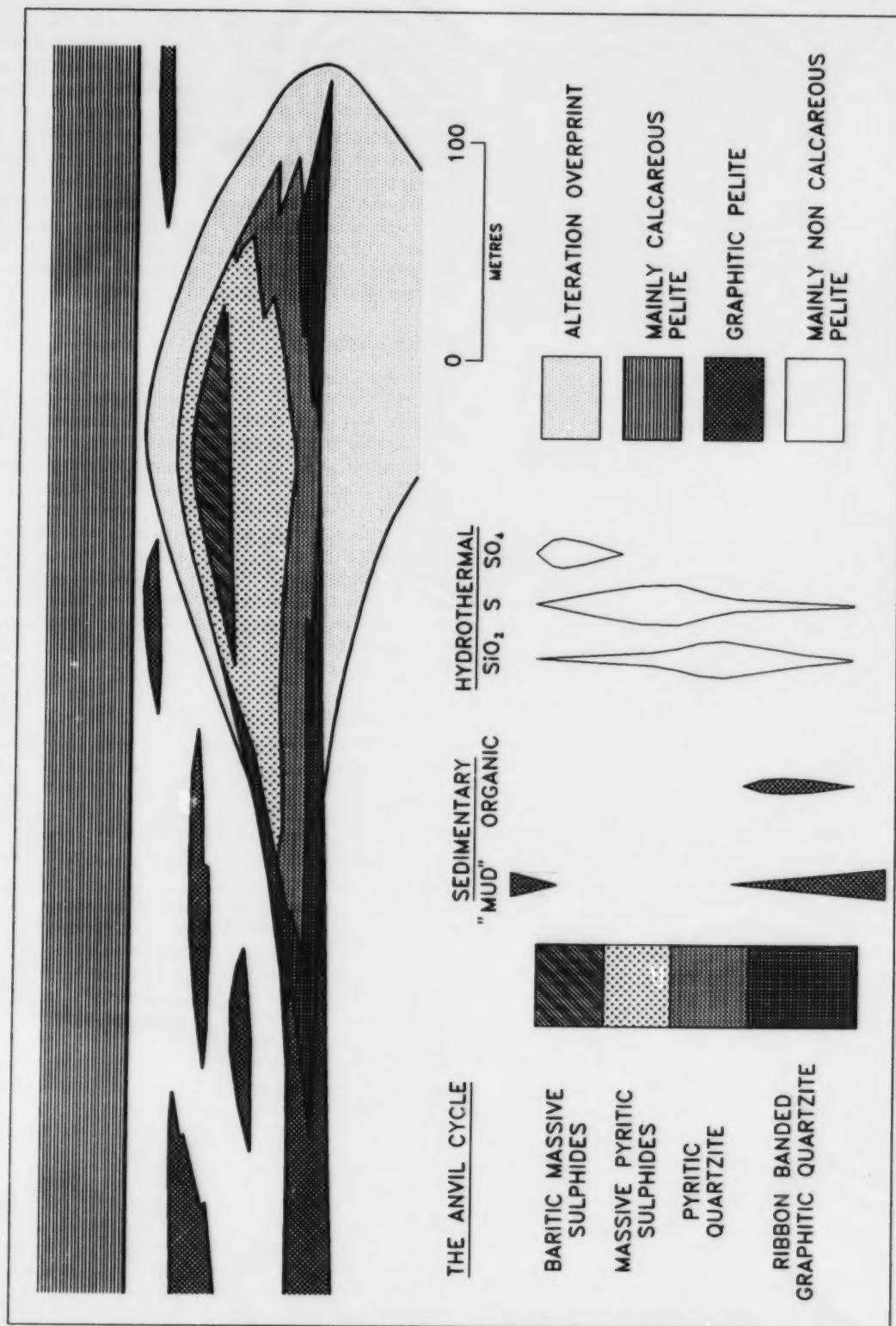


Figure 3-13. Idealized Anvil deposit showing relation of different ore facies and host rocks.
 From Jennings and Jilson, 1986.

cyclical precipitation within restricted basins over an extended period of time. The Gataga deposits on the other hand appear to be related to a single pulse of mineralization.

Howard's Pass District

In the Howard's Pass district (Figure 3-15) delicate laminae of fine-grained sphalerite, lesser galena and minor pyrite occur in a sedimentary cycle that begins with laminated limestone and grades upward into laminated cherty mudstone and carbonaceous chert (Figure 3-16). The sulphide laminae are concentrated within saucer-shaped bodies. Morganti (1979) suggests these bodies formed in elongate sea floor depressions that parallel the base of the shelf to platform rise.

The X-Y and Anniv are the largest of the deposits along the 20 kilometre extent of the Howard's Pass district (Figure 3-15). Collectively these deposits contain drill-indicated reserves of 113 million tonnes of 5 per cent zinc and 2 per cent lead (Dawson *et al.*, in press). The deposits are laterally extensive but relatively low grade. In contrast to other sedimentary exhalative deposits, barite and silver content are very low. The lack of barite suggests anoxic conditions; low silver may reflect low temperature of formation. The lack of sulphide zoning and stringer mineralization, the finely laminated nature of the ore, and the presence of sedimentary intercalations also support a model of slow sulphide accumulation within an anoxic, restricted marine basin.

Regionally, there is little evidence of an Early Silurian rifting event, although a short-lived marine transgression is recognized in the Kechika trough. Here a thin stratigraphic succession nearly identical to that of the Howard's Pass district unconformably overlies Middle to Late Ordovician graptolitic shales. Deposition of starved-basin chert and graphitic shale was terminated by influx of dolomitic detritus that heralded the start of a major marine regression and erosion of platform carbonates surrounding Selwyn Basin and Kechika trough.

Maxi

The Maxi deposit is located south of the Howard's Pass district, in the vicinity of Frances Lake. Intensely deformed siliceous graphitic phyllites of the Road River Group host the mineralization. The age of these rocks is uncertain; they may be either Ordovician or Early Silurian (Blusson, 1978). The mineralized zone includes laminations of coarse-grained sphalerite, lesser galena and quartz. Several Devonian age deposits occur nearby suggesting multiple mineralizing events in the district.

Gataga District

Sedimentary-exhalative deposits also occur in Early Silurian limestone, cherty mudstone and car-

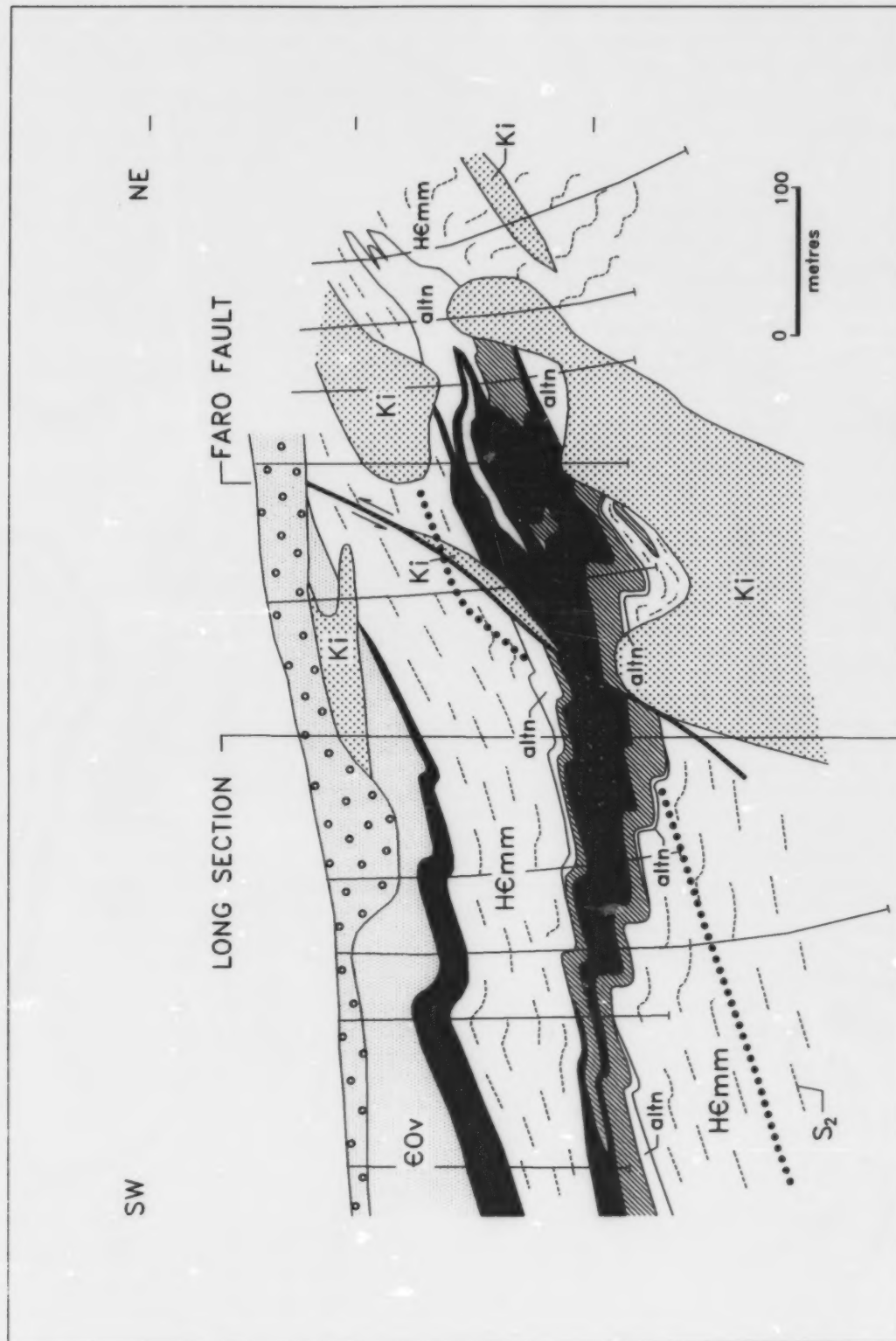
bonaceous shale of the southern Gataga district (MacIntyre, 1983). However, these deposits are relatively small and less sulphide rich than those of the Howard's Pass district. At the Ern prospect, an unusual stratabound zone of brecciated dolomite and quartzite that has been healed by massive pyrite, is interbedded with thin-bedded cherty mudstone, minor barite and sphalerite. The breccias are probably related to slumping along a submarine fault scarp. To the east and closer to the platform margin is the CT property. Here, a laterally extensive baritic zone up to three metres thick, with local massive pyrite-sphalerite and pyrite-sphalerite healed dolomite breccia occupies a similar stratigraphic position. As at the ERN, the breccias may be fault-scarp deposits.

EARLY-MIDDLE DEVONIAN

A thick succession of brown-weathering bioturbated dolomitic siltstone and thin-bedded dolostone typically sits unconformably on Early Silurian chert and black shale. The dolomitic siltstones were deposited during a major marine regression or regional uplift that resulted in partial filling of the Selwyn Basin and Kechika trough during Middle Silurian to Early Devonian time. The dolomitic detritus was probably derived from platform carbonates exposed east of the basin. This period of basin-filling was not favourable for formation of sedimentary-exhalative deposits. However, by Early Devonian time a starved-basin regime was once again established as indicated by widespread formation of pelagic and reefal limestone and deposition of carbonaceous black chert and shale. At least two deposits are believed to be of Early to Middle Devonian age — the Angie deposit in the Pelly Mountains of the Cassiar Terrane and the Vulcan deposit south-east of the Howard's Pass district.

The Vulcan deposit has been described in detail by Mako and Shanks (1984). Mineralization includes beds of laminated and massive pyrite-sphalerite-galena and coarse grained, planar veins of barite-fluorite-galena that are hosted by probable Early Devonian black shales of the Road River Group. The deposit is close to the Selwyn Basin-Mackenzie platform transition. Abrupt facies changes, synsedimentary faults, debris flows, local unconformities and the presence of high-potassium mafic flows within the host succession are evidence of extensional tectonics during Road River time.

The Angie occurrence is the largest of several deposits found in Early or Middle Devonian sooty limestone southwest of the Tintina fault. The deposit has unusual mineralogy with sphalerite, smithsonite, and native silver present as pelletoidal disseminations concentrated in bedding parallel bands and as secondary replacement and vein fillings (Abbott *et al.*, 1986).



Figures 3-14a and 3-14b. Longitudinal and cross sections through the Faro deposit. Black is massive sulphide, black to dark grey layer between COv and Hemm is graphitic phyllite, coarse stipple is quartzose disseminated sulphide. Hemm — Hadrynian to Cambrian Mount Mye Fm.; COv — Cambrian to Ordovician Vangorda Fm., Ki — Cretaceous granitic intrusion. From Jennings and Jilson, 1986. Figure 3-14b on following page.

MIDDLE DEVONIAN-MISSISSIPPIAN

Some of the world's largest sedimentary-exhalative deposits are hosted by Devonian-Mississippian rocks; for example, Meggen and Rammelsberg in West Germany, Tynagh, Silvermines and Navan in Ireland and the giant Red Dog in Alaska. During this time there were extensive intracratonic basins rimmed by carbonate banks. This regime ended with a worldwide episode of rifting, local magmatic activity and formation of sedimentary-exhalative and possibly Mississippi Valley-type massive sulphide deposits.

In the outer miogeocline of Selwyn Basin and Kechika trough, Early Devonian transgressive shale and siltstone is unconformably overlain by blue-grey weathering siliceous shale and carbonaceous chert of the Middle to Late Devonian lower Earn Group (Gordey *et al.*, 1982). These rocks were deposited in local fault-bounded starved-basins or rift troughs. In the Gataga district linear patch reefs grew on the uplifted edges of tilted fault blocks further restricting circulation within the basin. Basinal sedimentation was characterized by high concentrations of biogenic silica, carbon, barium and iron and relatively low amounts of clastic material. These sediments typically contain laminae and nodules of barite, pyrite and carbonate, all of which are considered positive indicators of a favourable depositional environment for sedimentary-exhalative deposits.

Some of the largest and most economically important sedimentary-exhalative deposits are hosted by the Earn Group including the Tom and Jason of the Macmillan Pass district and the Cirque (Stronsay) of the Gataga district. Numerous stratiform barite deposits also occur in this stratigraphic interval implying a genetic link between the deposit types. Coarse clastic beds are locally found within starved-basin sediments of the lower Earn group and some of these may be derived by slumping along fault scarps bounding the second and third order basins.

The timing of sedimentary-exhalative mineralization in Selwyn Basin and Kechika trough is roughly coincident with the early stages of a major tectonic event that greatly modified the pattern of continental margin sedimentation from Alaska to Mexico. Known as the Caribooan or Antler orogeny (Gordey *et al.*, 1987; Struik, 1981, 1987), it is recognized in Selwyn Basin and Kechika trough by the sudden appearance of coarse clastic turbidites derived, for the first time, from westerly and northerly source areas (Figure 3-17). Within the outer miogeocline, rapid facies changes, eastward-prograding clastic wedges of chert-pebble conglomerate, slump breccias and anomalous thickening of sedimentary sequences are typical of the upper Earn group and are evidence of extensive uplift and erosion along the western margin of the basin. Similar prograding clastic wedges are found in the Cassiar Terrane, and in the Kootenay Terrane alkalalic volcanics and related plutons were emplaced.

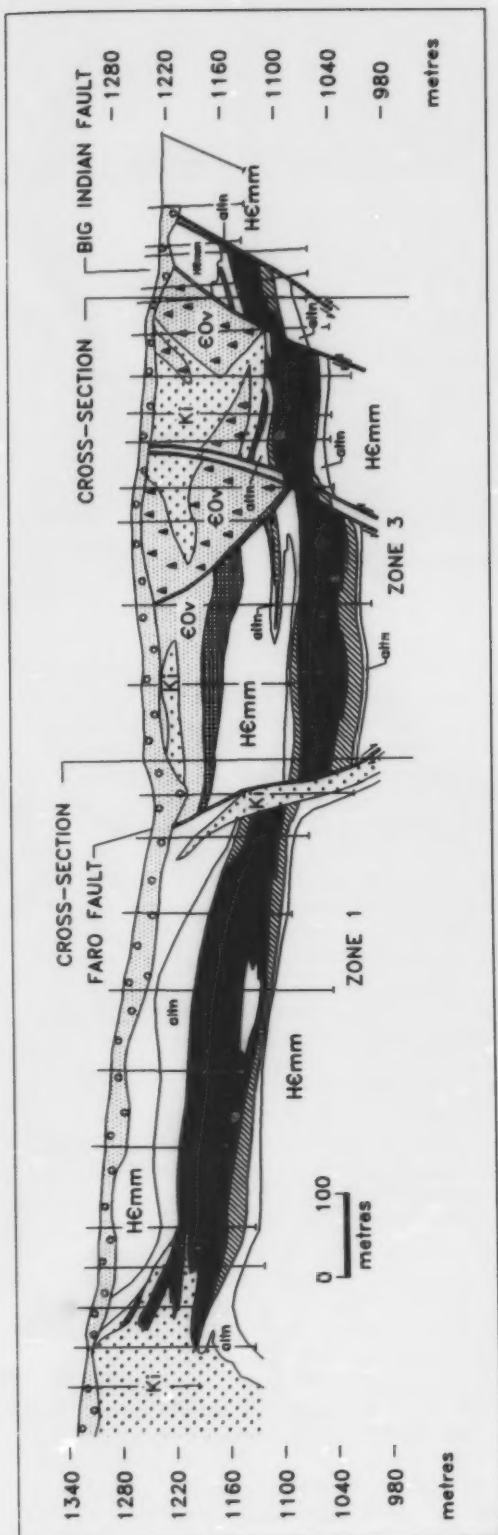


Figure 3-14b.

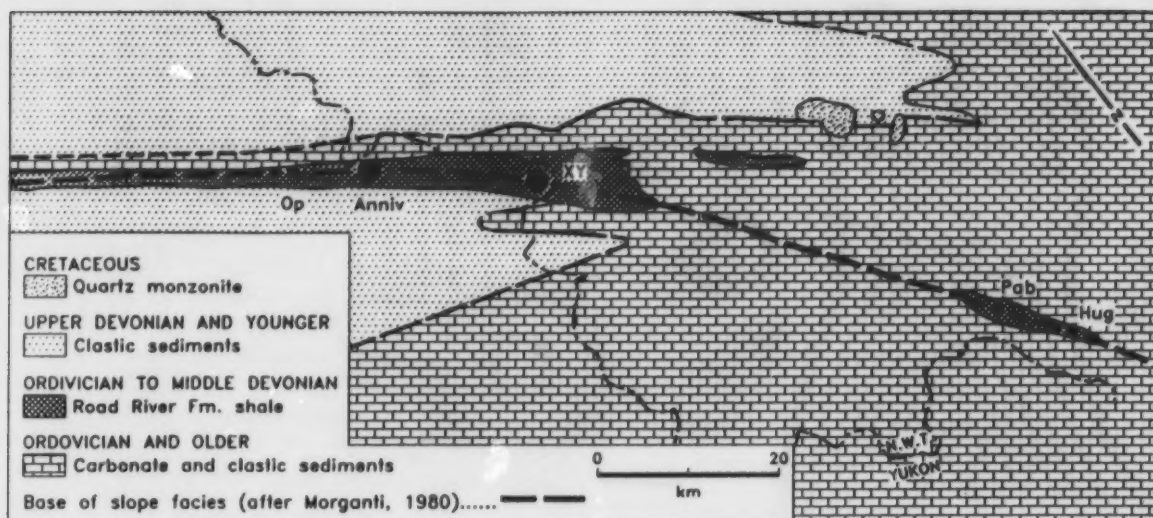


Figure 3-15. Simplified geology of the Howard's Pass district. From Came and Cathro, 1982.

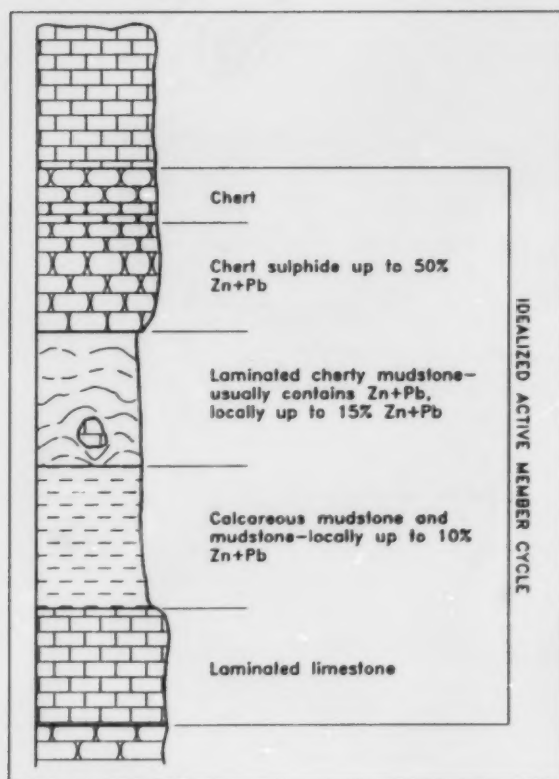
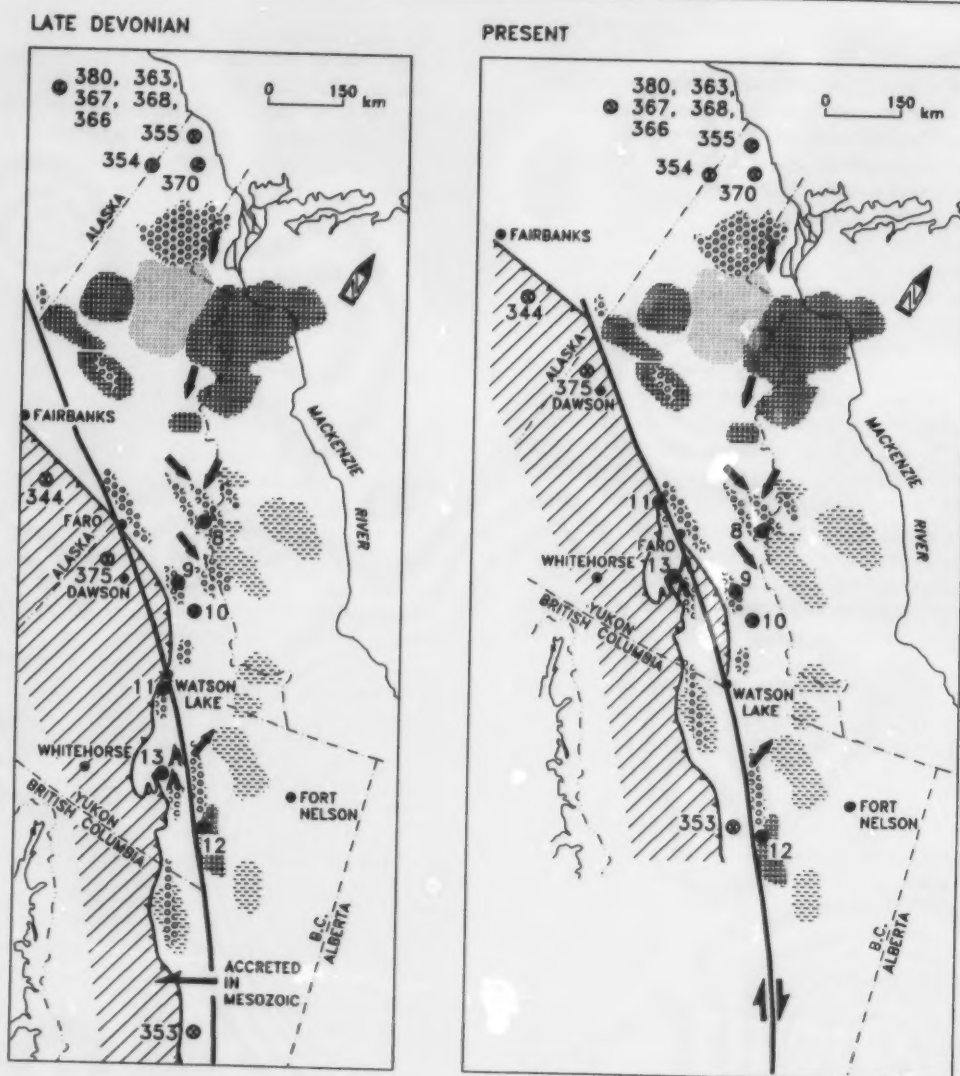


Figure 3-16. Stratigraphic column showing idealized active member cycle in the Howard's Pass district. From Morgantli, 1981.

Contemporaneous with uplift and coarse clastic sedimentation in the outer miogeocline, fine-grained clastic sediment of the Besa River Formation advanced progressively eastward across the carbonate platform (Pelzer, 1966; Taylor and MacKenzie, 1970). This onlapping of shale may be related to an eastward advancing front of basinal subsidence and rifting that occurred in Late Devonian to Mississippian time. Formation of sedimentary exhalative and Mississippi Valley-type massive sulphide deposits may have been triggered by this subsidence and rifting.

The change to coarse clastic sedimentation during the Late Devonian to Early Mississippian has been attributed to rifting (Tempelman-Kluit, 1979), strike-slip faulting (Eisbacher, 1983) and collisional orogeny (Gabrielse *et al.*, 1982). Trace element signatures of felsic metavolcanics in the Pelly Mountains most closely resemble those of peralkaline volcanics found in extensional environments supporting a rifting origin (Mortenson, 1982).

Granitic intrusions and related felsic volcanics in the Brooks Range of Alaska and the Pelly Mountains east of the Tintina fault give Devonian and Mississippian radiometric ages (Figure 3-17), as do similar intrusions in the vicinity of Adams Lake. This suite of Devonian-Mississippian intrusive and extrusive rocks may represent the remains of a magmatic arc that formed along the rifted continental margin. Coarse clastics of the upper Earn Group may have been derived by erosion of this rising arc (Gabrielse, 1981). Thin tuff beds intercalated with Earn Group rocks of the Kechika trough are further evidence of volcanic activity west of the trough.



- MAINLY CHERT CONGLOMERATE WITH SANDSTONES, SILTSTONE AND SHALE. IN NORTHERN YUKON, NONMARINE IN PART.
- MAINLY SANDSTONE, SILTSTONE AND SHALE OF THE IMPERIAL FORMATION
- SILTSTONE AND SHALE
- MAINLY SHALE, LESSER SILTSTONE, AND MINOR SANDSTONE
- FELSIC VOLCANIC ROCKS
- RADIOMETRIC AGES OF INTRUSIONS AND VOLCANIC ROCKS
- MACMILLAN PASS DISTRICT
- FIN OCCURRENCE
- MATT BERRY OCCURRENCE
- CLEAR LAKE DEPOSIT
- GATAGA DISTRICT
- MM DEPOSIT, BNOB, CHZERPNOUGH, JOE OCCURRENCE

Figure 3-17. Late Devonian paleogeography and location of radiometric ages from middle Paleozoic intrusions and volcanic rocks. From Abbott et al., 1986. See text for detailed explanation.

MacMillan Pass District

A cluster of early-Late Devonian (Frasnian) sedimentary exhalative and bedded barite deposits occurs in the MacMillan Pass district of the Yukon. Bedded barite deposits of late-Middle Devonian and early Mississippian age (Dawson and Orchard, 1982) are also present. The deposits occur within and peripheral to a structurally modified northwest-trending graben. The graben, which contains up to 1000 metres of deep marine carbonaceous chert, channel conglomerate and thin bedded silty turbidite of the Lower Earn Group (Abbott, 1982), contains a small pull-apart basin near its southern margin (Abbott and Turner, 1990; Turner and Einaudi, 1986). Three sedimentary exhalative deposits, — Jason End, Jason South/Main and Tom occur adjacent to northeast-trending normal faults of the pull apart basin (Figure 3-18).

Sedimentary breccias are intercalated with the ore-bearing sequences suggesting fault movement and scarp slumping accompanied exhalative activity. Minor basaltic lava and tuff is also found within the graben particularly near north-trending fault zones.

Numerous stratiform barite deposits occur peripheral to the central pull apart basin (Figure 3-18). These deposits may have formed by exhalation of lower temperature, barium-rich fluids into a relatively shallow, oxygenated water column.

The Jason South/Main deposit has been described in detail by Bailes *et al.* (1986) and Turner, (1990). Turner's work suggests the two orebodies, South and Main, are part of the same deposit. Figure 3-19 shows a restored stratigraphic cross-section through the deposit. The Jason South/Main deposit is interbedded with scarp breccias, distal turbidites and carbonaceous shales that stratigraphically overlie channel conglomerates. The isotopic geochemistry of the deposit has been studied by Longstaffe *et al.* (1982), Gardner and Hutcheon, (1985) and Turner (1990).

The Jason deposit includes both a veined and massive iron carbonate-sulphide zone adjacent to the Jason fault and a distal, finely laminated barite, sulphide and chert facies. Ferroan carbonate alteration has been superimposed on and replaced the stratiform mineralization near the vent zone. Cross-cutting mineralization includes a discontinuous zone of brecciated, silicified and carbonatized rock cut by veinlets of quartz, ankerite and lesser galena, sphalerite, chalcopyrite and pyrrhotite (Bailes *et al.*, 1986; Turner, 1990). This mineral assemblage and the well-developed, fault-controlled stockwork and breccia zones associated with the deposit suggest a relatively dynamic, high temperature hydrothermal system.

The Tom deposit is well-zoned with a copper-silver rich stockwork feeder zone underlying a galena-sphalerite rich massive sulphide body that grades vertically and laterally into laminated sphalerite and

pyrite and distally to mixed barite and sulphide (Carne, 1979; McClay and Bidwell, 1986; Goodgellow and Rhodes, 1990). This zoning is attributed to seawater mixing and cooling of a relatively low temperature brine that was exhaled into anoxic bottom waters along an active fault zone (McClay and Bidwell, 1986).

Another deposit of interest in the MacMillan Pass district is the large tonnage, low grade Boundary Creek or Nidd deposit recently described by Turner and Rhodes (1990). Quartz, ferroan carbonate, pyrite, minor sphalerite and trace galena occur within conglomerate, muddy conglomerate, diamictite and volcanic rocks adjacent to a Late Devonian syndepositional fault. The mineralization occurs as cement in lower Earn Group conglomerate and diamictite, as veins and replacements within silicified and ferroan carbonate altered rocks and as large banded sphalerite-carbonate veins and carbonate breccias along the fault (Turner and Rhodes, 1990). This shallow-level epigenetic alteration and mineralization is believed to be contemporaneous with magmatism and formation of stratiform zinc-lead deposits in the district.

Other Selwyn Basin Deposits

Several other Late Devonian or Mississippian deposits are found outside of the MacMillan Pass district. The most notable of these are the Matt Berry (Ikona, 1977) and Fin (Lane, 1980) occurrences in the Frances Lake area and the Marg deposit (Turner and Abbott, 1990) located along the northern margin of the Selwyn Basin.

The Marg is a folded Zn-Pb-Cu-Ag-Au massive sulphide deposit that is hosted by ferroan-carbonate altered black siliceous phyllite, quartz-sericite-chlorite-schist and quartzite of Early Mississippian age (Turner and Abbott, 1990). Sulphide minerals include pyrite, sphalerite, galena, chalcopyrite and trace tetrahedrite and arsenopyrite. Quartz phytic metavolcanic rocks underlie the massive sulphide. A paleo-vent is defined by the distribution of ferroan carbonate. Away from the paleo-vent volcanics are altered to sericite-quartz or chlorite-quartz schists.

The mixed volcanic-sedimentary succession containing the Marg deposit unconformably overlies Proterozoic grits along the northern margin of the Selwyn Basin. This tectono-stratigraphic setting and volcanic association distinguishes this deposit from others in the Selwyn Basin. The location of volcanic centres and associated hydrothermal activity may have been controlled by major rifts along the basin to platform transition although there is no direct evidence for this.

Gataga District

Sedimentary exhalative deposits occur in Middle Ordovician, Early Silurian and Late Devonian to Mississippian basinal facies rocks of the Kechika trough

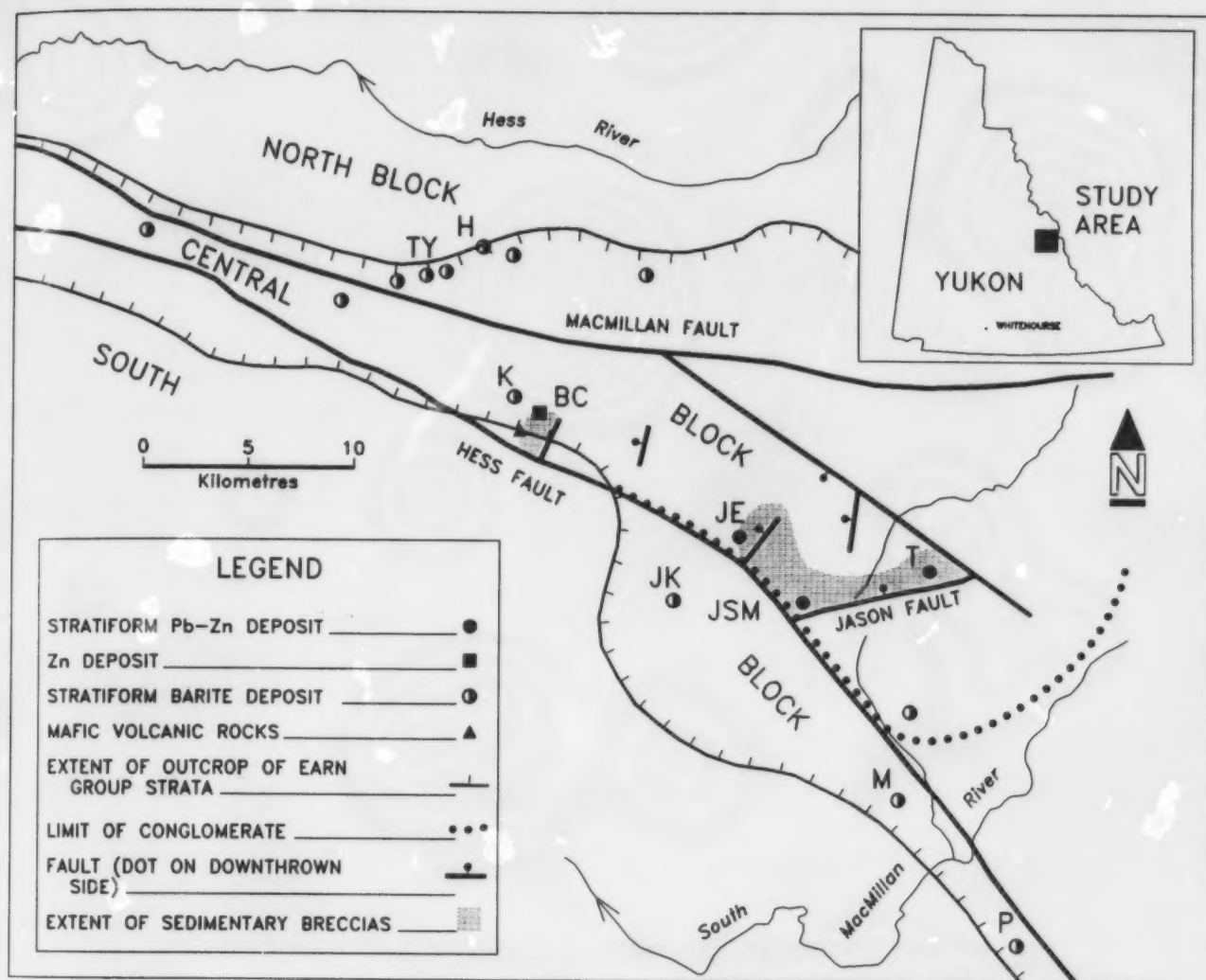


Figure 3-18. Tectonic elements and location of mineral deposits, Macmillan Pass district. Zinc-lead prospects noted on map are Boundary Creek (BC), Jason End (JE); Jason South/Main (JSM) and Tom (T). Barite prospects are Tyrula (TY), Hess (H), Walt (W), Kobuk (K), JK (JK), Gary (G), Moose (M) and Pete (P). From Turner and Rhodes, 1990

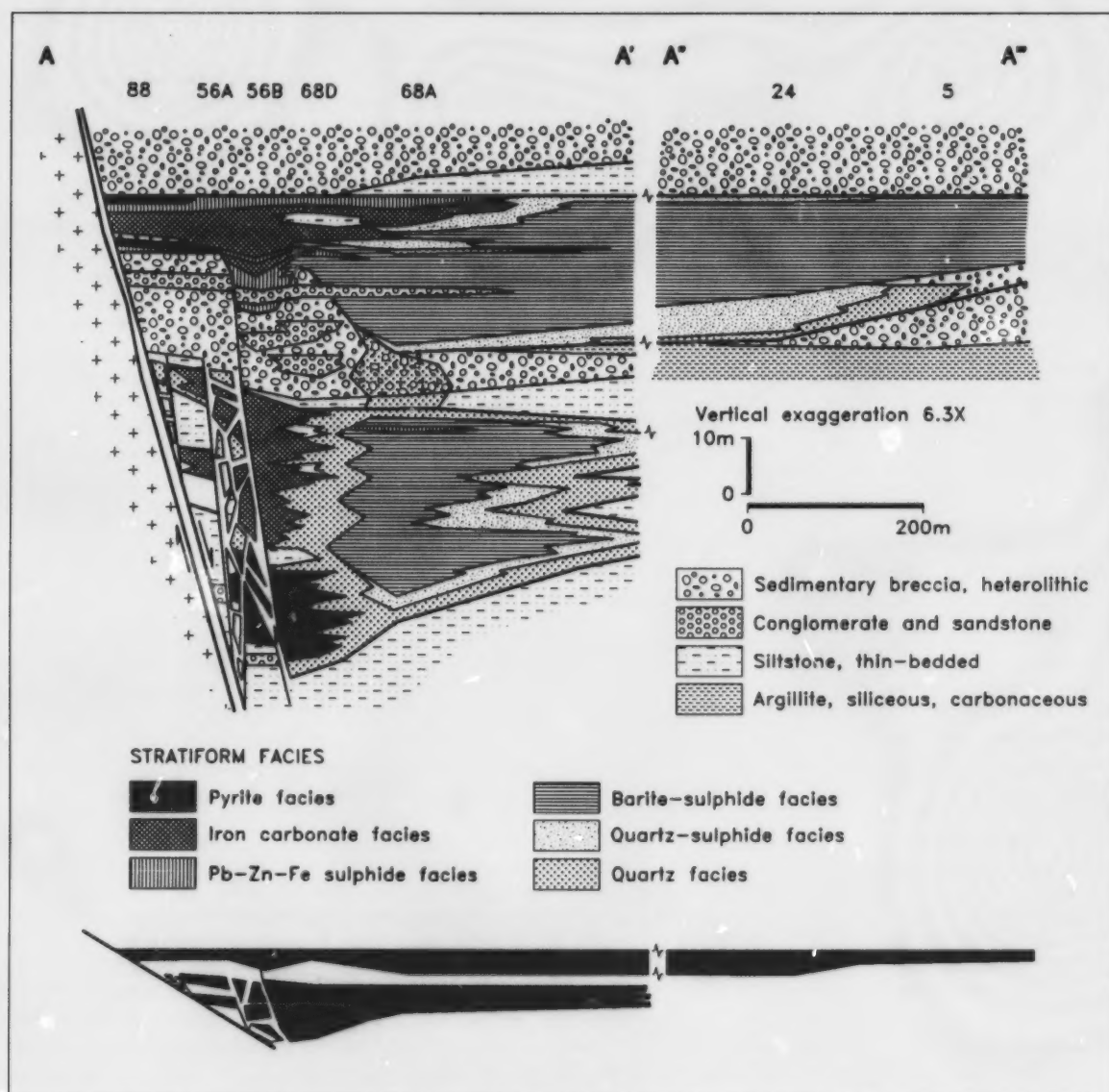


Figure 3-19. Restored stratigraphic cross section through the Jason South/Main deposit. Plus pattern is chert. From Turner et al., 1989.

(Figure 3-21), a southeast extension of the Selwyn Basin (Taylor *et al.*, 1979). The most economically significant of these deposits, which collectively define the Gataga mineral district (MacIntyre, 1982; 1983; in press), are early-Late Devonian in age (Irwin and Orchard, 1989).

The Late Devonian barite-sulphide deposits of the Gataga district occur within distinctive blue-grey weathering black carbonaceous chert, cherty mudstone, argillite, siliceous shale and siltstone of the Gunsteel Formation (Figure 3-20). Regionally the host sequence is characterized by nodules and lami-

nae of barite (Plate 3-2) and pyrite. This distal facies grades into bedded barite that may or may not contain laminae of pyrite, sphalerite and galena (Plate 3-3). Based on lithology and age the host rocks are correlated with the lower Earn Group of the Selwyn Basin (MacIntyre, 1983). In addition to the Cirque (Stronsay), other important prospects in the district include Driftpile Creek, Bear, Mt. Alcock, Pie, Fluke and Elf. The Kwadiacha is a large bedded barite deposit close to the basin to shelf transition zone (MacIntyre and Diakow, 1982). East of the district, numerous Mississippi Valley-type deposits occur in

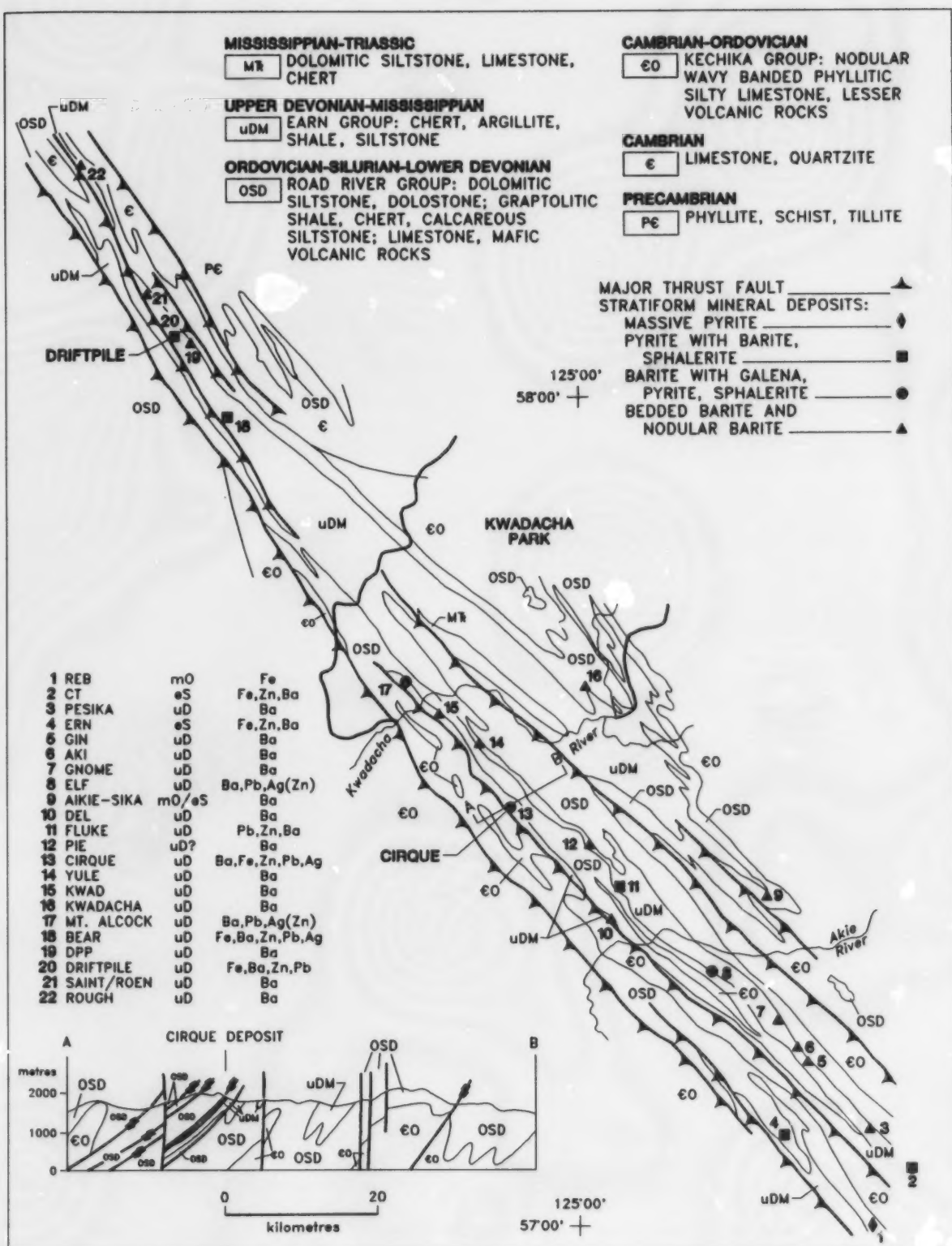


Figure 3-20. Geology of the Gataga District, northeast B.C. From MacIntyre, 1983.



Plate 3-2. Nodules of barite in a dark grey carbonaceous cherty argillite, Gunsteel Formation, Galaga District, northeast British Columbia.



Plate 3-3. Laminae of galena (white) in a dark grey barite host, Mt. Alcock prospect, Galaga District.



Plate 3-4. Finely laminated pyrite with laminae disrupted by diagenetic growth of carbonate nodules (black), Driftpile Creek prospect, Gataga District.



Plate 3-5. White barite laminae disrupted by soft sediment deformation, Driftpile Creek prospect, Gataga District.

and often show evidence of soft sediment deformation. McClay *et al.* (1989) have described their stratigraphic and structural setting and suggest mineralization occurs at more than one stratigraphic level.

Red Dog

The Red Dog zinc-lead-silver deposit is located in the northwestern corner of Alaska. This very large, high grade deposit, recently brought into production by Cominco Ltd., is included in this compilation because it is an excellent example of the economic potential of this class of mineral deposit. The deposit has been described briefly by Moore *et al.* (1986).

The Red Dog is hosted by black siliceous shale and chert of the Mississippian to Permian Kuna Formation. Reconstruction of the original geometry of the deposit is difficult because the deposit occurs as a series of stacked thrust plates. According to Moore *et al.*, the second order stratigraphic basin in which

the deposit occurs is defined by the extent of light gray micrite and dark gray calcareous shale of the Kivalina Member that underlies the mineralized interval.

The ore zone includes sulphide-bearing silica exhalite, semi-massive sulphide, massive sulphide and sulphide-bearing barite (Figure 3-23). Sulphides, in decreasing order of abundance, include sphalerite, pyrite, marcasite and galena. The sulphides are massive and generally lack the fine lamination characteristic of other sedex deposits. Sphalerite contains rare chalcopyrite and pyrrhotite inclusions and boulangerite sometimes occurs as inclusions in galena. Feeder veins are observed at the base and at the periphery of the deposit but the original position and orientation of these veins is uncertain due to the structural complexity of the deposit. Thin pyrobitumen-calcite veins form the latest stage fracture filling.

Barite also occurs in overlying strata of the Permian Siksikpuk formation. Sedimentary-exhalative mineralization of this age is not known in the Canadian Cordillera although Permian age cherts are widespread and are part of a starved-basin succession that succeeded the Earm Group.

According to Moore *et al.* (1986) the deposit formed during the early stages of a long period of starved basin sedimentation. Mineralization apparently occurred episodically from Early Mississippian to Pennsylvanian or Permian time. Tectonic instability is indicated by abrupt facies changes within the host basin. Small igneous intrusions of possible Mississippian age are evidence for elevated heat flow during basin subsidence. Permeable Devonian fluvial deltaic rocks may have provided a basin aquifer through which the mineralizing fluids moved prior to exhalation onto the seafloor.

Cassiar and Kootenay Terrane deposits

Mississippian alkalic volcanic rocks in the Pelly Mountains, southwest of the Tintina fault host several small stratiform massive sulphide and bedded barite deposits. These deposits occur in a thrust panel of submarine volcanoclastic rocks and trachytic lava flows that are intercalated with black shale and intruded by coeval hypabyssal syenite plugs (Abbott *et al.* 1986; Morin, 1977). The deposits are classified as volcanogenic and have many of the features of the Kuroko class of deposits (Mortenson and Godwin, 1982).

The MM is the largest of the Mississippian volcanogenic deposits and consists of several thin lenses of massive pyrite, pyrrhotite and varying amounts of galena, sphalerite, chalcopryrite, and quartz. The sulphide lenses are located on the flanks of a trachyte plug. The trachyte is locally strongly fractured and cut by quartz, chlorite, pyrite and chalcopryrite stringers. Barite and pyrite content of the mineralized horizons increases away from the plug.

The MM deposit is located within the Cassiar Terrane. If the displacement on the Tintina fault is on the order of 450 kilometres as shown in Figure 3-17, then the MM deposit and associated volcanic rocks would have been located immediately west of the Gataga district. This suggests an arc-back arc configuration was established in Late Devonian to Mississippian time, at least along this part of the continental margin.

Devono-Mississippian metasedimentary and metavolcanic rocks of the Eagle Bay assemblage, which host the Rea and Homestake volcanogenic deposits (Höy and Goutier, 1986), may also represent the remains of an early arc. Plutonic rocks of this age are also found in the Adams Lake area, at various localities within the Cassiar Terrane, and in the Brooks Range of Alaska, further evidence of significant magmatic activity along the continental margin in Devono-Mississippian time.

The combination of widespread rifting and local magmatic activity during Late Devonian-Early Mississippian time makes this period extremely favourable for both sedimentary exhalative and volcanogenic massive sulphide deposits.

GENETIC MODELS

The geologic characteristics and genetic models for sedimentary exhalative deposits have been reviewed by Gustafson and Williams (1981), Large (1980, 1981, 1983), Morganti (1981) and others. The physiochemical controls on formation of the deposits have been discussed by Finlow-Bates (1980), Russell *et al.* (1981), Russell (1983), Lydon (1983), Lydon *et al.* (1986), and Goodfellow and Jonasson (1986a,b). The consensus amongst these authors is that the deposits form by the precipitation of sulphide and sulphate minerals from metalliferous brines that were exhaled along active submarine faults. Metals and fluids are most likely derived from the sedimentary pile either by normal dewatering during basinal subsidence or by hydrothermal leaching during periods of elevated heat flow and convective circulation of seawater through the sedimentary pile (Cathles, 1986; Badham 1981; Russell, 1983).

MODERN SUBMARINE EXHALATIVE SYSTEMS

Two modern day submarine exhalative systems are often cited as examples of the processes that may have formed ancient sedimentary-exhalative deposits — hydrothermal venting at sedimented rifts such as Guaymas Basin and Middle Valley and the brine pools of the Red Sea. The former involves hydrothermal discharge into ambient seawater and dispersal of sulphide particulate. Sulphide mounds grow by chimney growth at vents followed by collapse and replacement (Koski, 1986). Such discharge may overlie active sill emplacement into the wet sediment pile as at Guaymas Basin. Recharge of the convection cell may take place along the faults bounding the pull apart basin. Although this vent complex dominant model appears valid for some sedimentary-exhalative deposits such as Red Dog, it may not be applicable to fine-grained, laminated sulphide-barite of most SEDEX deposits. A more likely model is that many of the deposits, particularly those in starved marine sedimentary sequences, formed by alternating sulphide and sulphate precipitation from a metal-rich brine pool. In this model metal-bearing, heated brines that are more dense than ambient seawater are discharged from fault-controlled vents to form a ponded brine pool on the seafloor. Within the brine pool, discharged fluids rise as buoyant plumes that spread laterally below a density interface. Barite and sulphide are precipitated from this plume in response to the physiochemical conditions of the depositional basin, such as the availability of reduced sulphur. In this way thin lami-

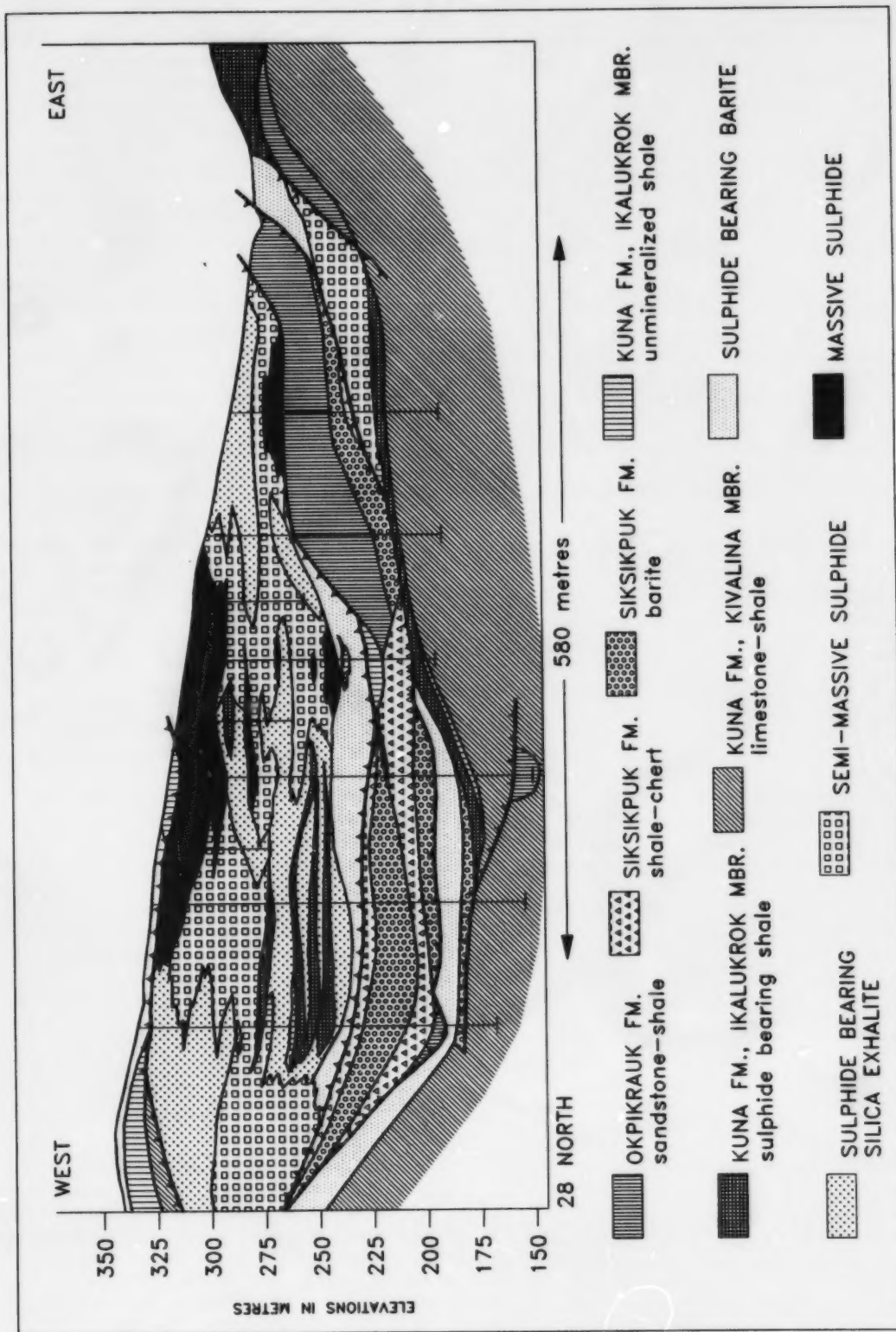


Figure 3-23. Cross section of the Red Dog deposit, Alaska. From Moore et al., 1986.

nae of barite and sulphide can be deposited over a relatively wide area. A modern example is the Atlantis II deep in the Red Sea system where brines are periodically exhaled into an anoxic brine pool within an axial deep and precipitate sulphide, oxide, sulphate and carbonate minerals in response to changing brine pool chemistry and the degree of mixing with the overlying oxic water column (Shanks and Bischoff, 1980; Zierenberg and Shanks, 1986). The brine pools have dissolved metal concentrations much in excess of reduced sulfur, are accumulating sediment at a rate of 100 centimetres per 1000 years (compared to 5 to 10 centimetres per 1000 years elsewhere in the Red Sea) and are devoid of any biologic activity. Areas of hydrothermal venting are characterized by epigenetic veins within the metalliferous sediment near the vent site and formation of epigenetic veins in underlying strata. Slump breccias and soft sediment deformation are triggered by tectonic activity along steep graben walls bounding the deep. A similar model (Figures 3-24; 3-25) is proposed for genesis of the Jason (Turner, 1990) and Cirque deposits (Pigage, 1986; MacIntyre, in press).

Although the brine pools of the Red Sea system are a plausible model for the depositional environment of many sedimentary exhalative deposits *e.g.*, Anvil, Macmillan Pass, Howards Pass, Gataga, it is not a good model for tectonic setting. The Red Sea is believed to be flooded by basaltic rocks and a sheeted-dike complex generated by formation of ocean crust along an axial rift trough. Also, the metalliferous sediments precipitated in the Atlantis II deep are copper and zinc rich and have low lead and barium concentrations. This probably reflects interaction of hydrothermal fluids with oceanic crust basalts that floor the trough, a conclusion that is also supported by isotopic ratios (Zierenberg and Shanks, 1986). Also, very high salinities of the Red Sea brine pools are a critical requirement for this model and are probably due to dissolution of evaporites within the area of fluid recharge.

ENVIRONMENT OF DEPOSITION

The variable nature of sedimentary exhalative deposits probably reflects the environment in which the brines were discharged. Carbonaceous shale or chert hosted deposits formed where fluids were discharged into a starved, deep-water anoxic seafloor sub-basin (Figure 3-25). Irish type carbonate-hosted SEDEX deposits, on the other hand formed where fluids were discharged into a shallower water shelf or lagoonal environment and Mississippi Valley-type deposits formed where metalliferous brines encountered open spaces in the carbonate substrata (Jackson and Beales, 1967). The close spatial association of Mississippi Valley and SEDEX deposit types, particularly in northeast British Columbia, suggests a common source of metals and fluids.

NATURE OF THE MINERALIZING FLUIDS

The source of transporting fluids and metals, fluid transport mechanisms and sources of reduced sulphur are the main points of variance amongst those working on sedimentary exhalative deposits. Given the differing sedimentary environments in which the deposits are found it is not surprising that there is no consensus. In fact, there is every likelihood that physiochemical conditions of the depositional environment varied considerably from deposit to deposit depending on where the site of exhalation was located. For example, a shallow carbonate shelf environment varies considerably from a deep marine starved basin even though the resultant mineral deposits may be similar.

SOURCE OF METALS

The source of the zinc, lead and barium that characterizes sedimentary exhalative deposits formed in intracratonic and marginal basins is believed to be the underlying sedimentary pile or crystalline basement rocks (Badham, 1981). This conclusion is based on the general absence of a magmatic source in most areas and the relatively radiogenic nature of lead and strontium in these deposits which suggests an upper crustal origin (Godwin and Sinclair, 1982; Godwin *et al.*, 1982; Modene and Ryan, 1986; Turner, 1990). Interaction of heated basinal fluids with clastic material derived from a cratonic source could produce radiogenic fluids rich in iron, lead, zinc and barium.

Lydon *et al.* (1986) have proposed a model for formation of the Macmillan Pass deposits that derives the mineralizing fluids and contained metals from the Hadrynian grit unit believed to lie 2 to 5 kilometres below this part of Selwyn Basin. Elsewhere in Selwyn Basin, extensive albitization of feldspar in the grit unit has been observed suggesting this unit may have acted as a permeable reservoir or aquifer for heated brines (Goodfellow and Jonasson, 1986a). The arkosic nature of these rocks suggests a high radiogenic lead background and therefore an excellent source rock for the lead found in sedimentary exhalative deposits. These grits also have radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ values similar to those found in carbonate and barite associated with sedimentary exhalative deposits, further supporting this hypothesis (Goodfellow and Jonasson, 1986a,b; Turner, 1990).

Westward prograding clastic wedges such as the Hadrynian grit unit were deposited along the rifted continental margin of the Canadian Cordillera. These rocks are typically truncated by sub-Cambrian to sub-Devonian unconformities where they onlap basement arches. This geometry would provide ideal fluid traps for formational waters.

The clustering of sedimentary exhalative and carbonate-hosted deposits in similar geographic

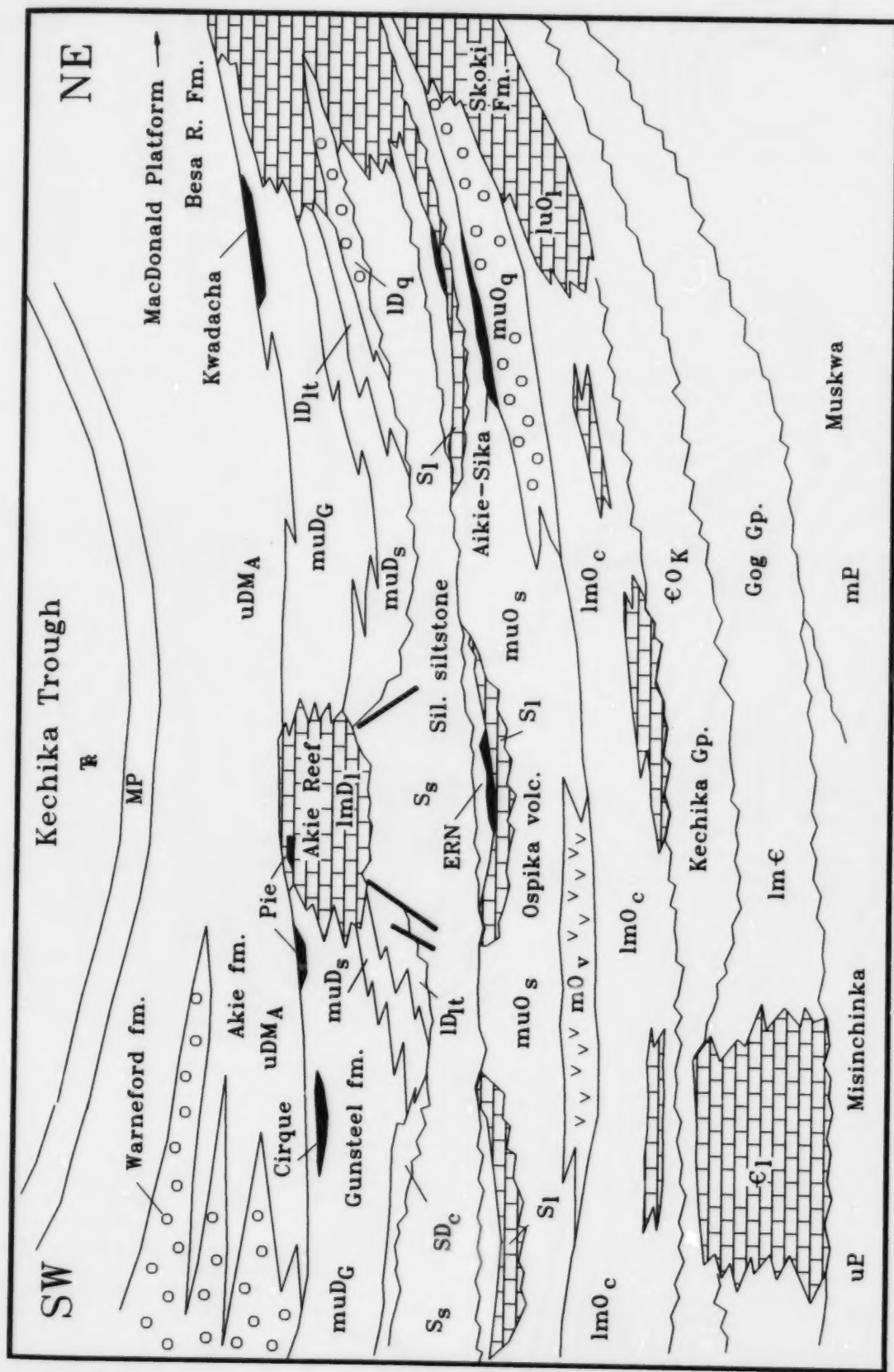


Figure 3-21. Idealized SW-NE section through the Kechika Trough showing stratigraphic position of SEDEX deposits, Galaga district, Northeast B.C.

carbonates of the MacDonald platform (MacQueen and Thompson, 1978)

The Cirque (Stronsay) deposit has geological reserves of 38.5 million tonnes averaging 8.0 per cent zinc, 2.2 per cent lead and 47.2 grams per tonne silver; the South Cirque contains 15.5 million tonnes averaging 6.9 per cent zinc, 1.4 per cent lead and 32 grams per tonne silver respectively. The geology and geochemistry of these deposits has been described by Jefferson *et al.*, (1983), Pigage (1986), and Gorzynski (1986).

The Cirque and South Cirque deposits occur within a southwest dipping panel or synclinal keel of carbonaceous cherty argillite, porcellanite and siliceous shale of the Middle to Late Devonian Gunsteel Formation (Figure 3-21). Dolomitic siltstone and black graptolitic shale of the Ordovician to Early Devonian Road River Group structurally overlie the Devonian host rocks as a series of imbricated thrust panels (Figure 3-22). A set of listric normal faults offsets early thrust faults.

Three mineral facies are recognized at Cirque and South Cirque — pyritic, baritic and laminar banded (Jefferson *et al.* 1983; Pigage 1986). The pyritic facies is predominantly interlaminated pyrite, sphalerite and galena with lesser barite. The baritic facies is predominantly barite with laminae of pyrite, sphalerite and galena. Laminar-banded pyrite occurs mainly in the hangingwall of the deposit and has low zinc and lead values. Unlike some other sedimentary exhalative deposits, barite is concentrated at the base of the deposit rather than at the top. However, this apparent relationship may be due to intense imbrication and isoclinal folding of the deposit. The barite-sulphide lense, which is up to 70 metres thick (tectonic thickening ?) thins laterally outward into barren bedded barite and finally into zones of nodular barite.

There is no direct evidence for syndimentary faults, footwall alteration or stringer zones at Cirque although a siltstone breccia in the ore zone may be related to slumping along a submarine fault scarp. However, recognition of such primary features would be difficult because of the high level of structural imbrication associated with thrust faulting. As these thrusts probably occupy ancient rifts in the basin, any evidence of a vent complex centred on the rifts would probably be destroyed by movement along the thrust fault.

The Cirque and South Cirque deposits, like those elsewhere in the Selwyn Basin and Kechika trough, probably formed in fault bounded seafloor depressions. The orientation of facies boundaries and variations in unit thicknesses suggest these subbasins were arranged along the axis of a northwest-trending half graben.

The Driftpile Creek deposits are similar to those at Cirque but are lower grade and do not contain appreciable silver. Here both barite (Plate 3-3) and sulphide facies (Plates 3-4 and 3-5) are finely laminated

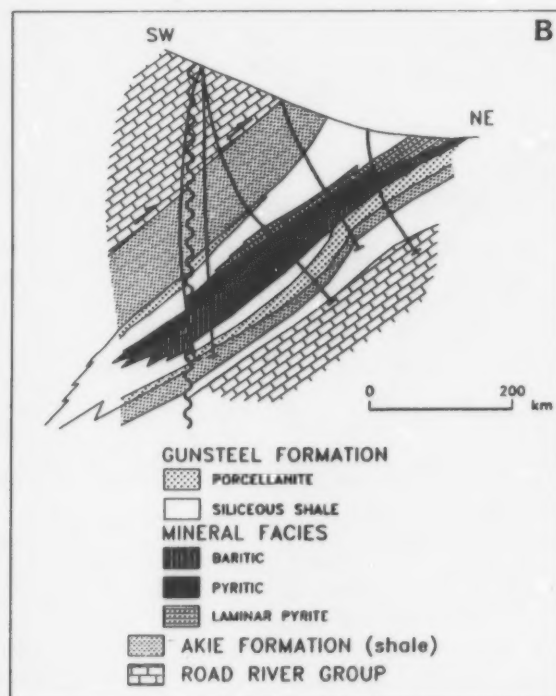
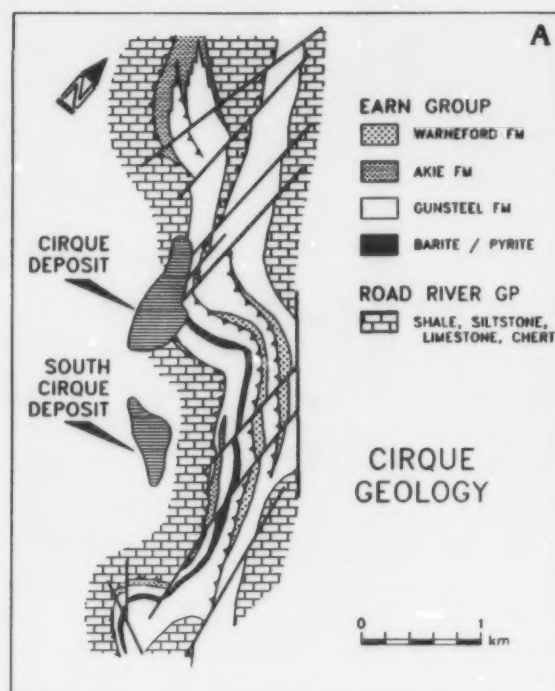


Figure 3-22 a. Simplified geology in the vicinity of the North and South Cirque deposits. From Jefferson *et al.*, 1983; b. Schematic cross section through the Cirque deposit. From Jefferson *et al.*, 1983.

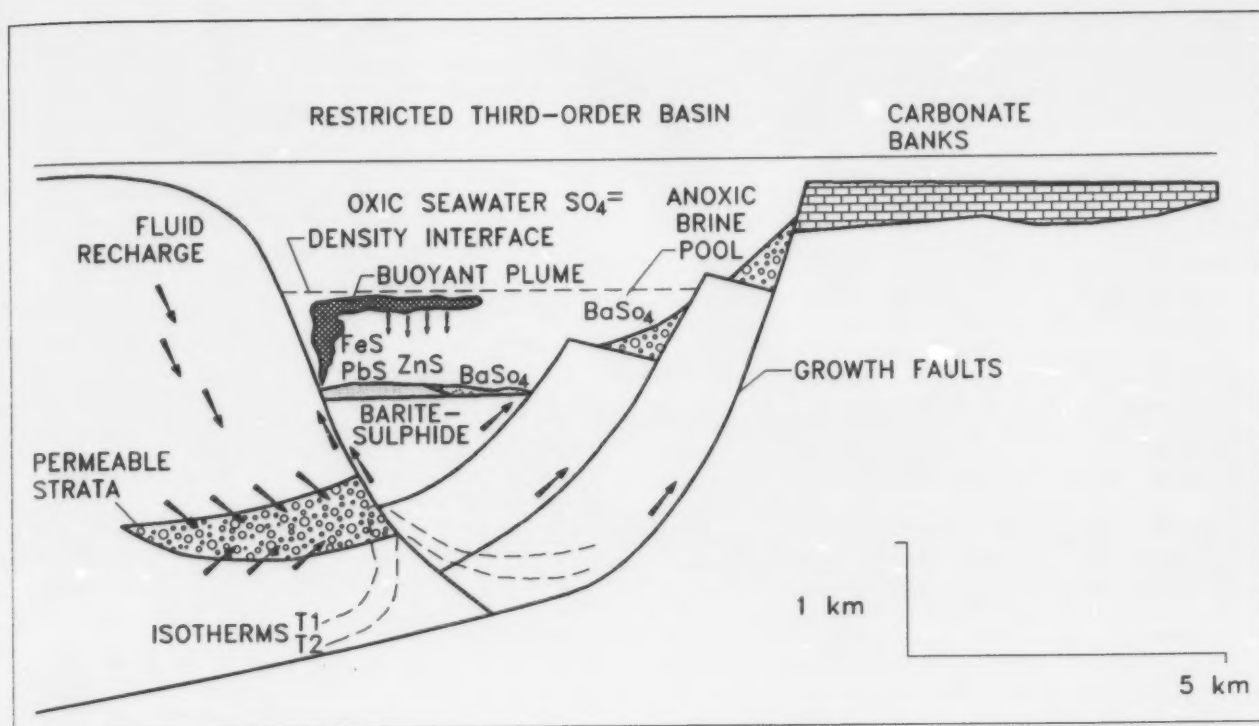


Figure 3-24. Interpretive model for formation of the Cirque deposit. Modified from a model for the Jason deposit (Turner et al., 1989).

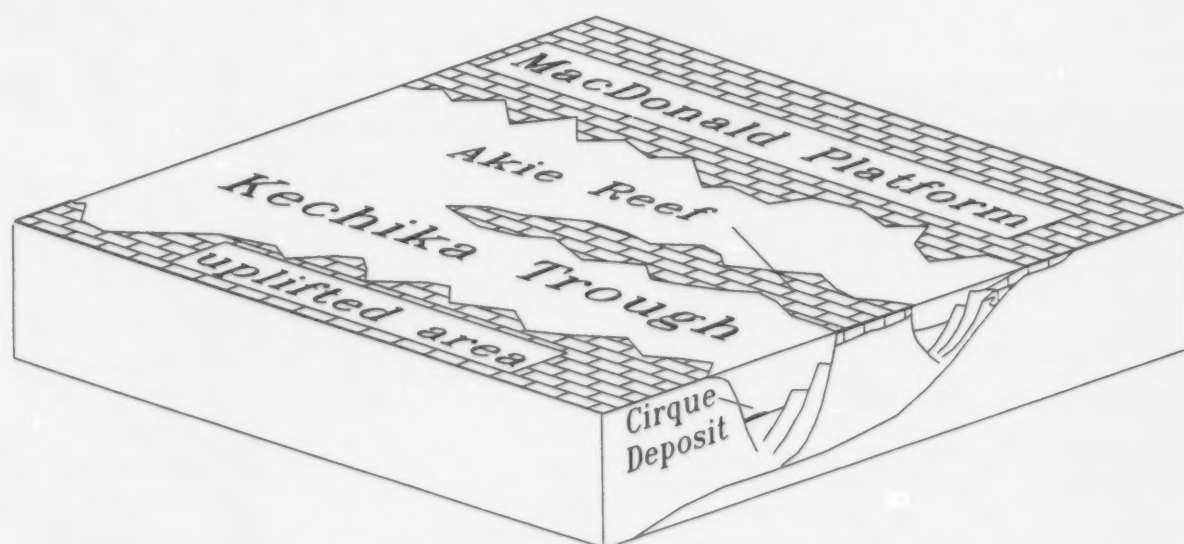


Figure 3-25. Late Devonian paleogeography of the Kechika trough and implied location of the Cirque deposit.

areas may reflect the extent of favourable brine reservoirs in the areas underlying these belts. More research into the nature of these possible reservoir rocks is required to further constrain a possible link with the formation of the mineral deposits.

SOURCE OF SULPHUR

Sedimentary exhalative deposits hosted by marine sedimentary strata typically have $\delta^{34}\text{S}$ values that are equal to or heavier than those determined for coeval seawater (Claypool *et al.*, 1980; Goodfellow and Jonasson, 1984; Cecile *et al.*, 1983). Heavy $\delta^{34}\text{S}$ values in sulphide and sulphate phases (Figure 3-26) are believed to be due to progressive reduction of sulphate to H_2S within a restricted, possibly stratified anoxic water column. The heavy values result from preferential removal of ^{32}S by formation of diagenetic pyrite and related phases. This model is consistent with the host lithologies of many sedimentary exhalative deposits which also indicate a starved, strongly reducing basinal environment.

Based on sulphur isotope analysis, Goodfellow and Jonasson (1986) concluded that the Howard's Pass deposits formed from moderate temperature (180°C), sulphur-poor, carbon dioxide-rich fluids discharged into an ambient sulphidic water column during several major pulses spanning 3 to 5 million years. A progressive increase in $\delta^{34}\text{S}$ in pyrite is interpreted to reflect progressive bacterial reduction of sulphate to sulphide within an anoxic, restricted basin. This is consistent with the high levels of organic carbon contained in starved-basin sediments hosting sedimentary-exhalative deposits.

Large (1980) interpreted the sulphur isotope data from the Tom deposit to indicate a seawater source for sulphur in both sulphides and barite. Morrow *et al.* (1978) reached a similar conclusion for Selwyn Basin and MacDonald platform barite and barite-fluorite deposits. Turner (1990) interprets higher $\delta^{34}\text{S}$ values in the vent complex of the Jason deposit to reflect a hydrothermal sulphur source or replacement of barite; however laminated sulphides and barite that compose most of the Jason deposit have lower $\delta^{34}\text{S}$ values and are interpreted as derived from ambient seawater (Gardner and Hutcheon, 1985; Turner, 1990). Mako and Shanks (1984) interpreted sulphur isotopes from the Vulcan deposit as indicating both sulphate and sulfide were derived from the exhaling brines. They also suggested reduction of sulfate was due to organic decomposition perhaps related to thermal maturation of hydrocarbons. Zierenberg and Schmidt (1988) report a narrow range of $\delta^{34}\text{S}$ values that cluster near zero per mil suggesting a magmatic source of sulphur for a major part of the Red Dog deposit. A seawater source for sulphur is also indicated for deposits of the Gataga district which typically have heavy $\delta^{34}\text{S}$ values for both sulphides and barite (Figure 3-26).

TEMPERATURE AND COMPOSITION OF THE FLUIDS

Sedimentary exhalative deposits typically have fine-grained sulphides and generally lack veining, making fluid inclusion studies difficult. Where such studies have been done the material sampled has usually been coarse-grained epigenetic vein minerals that are assumed to be related to stratiform sulphide deposition. In general, the studies that have been done indicate the mineralizing fluids were moderately to highly saline and in the 150 to 275°C range. Specifically, Mako and Shanks (1984) obtained salinities up to 26 weight per cent for fluid inclusions from the Vulcan deposit. Shaw and Hodgson (1986) report temperatures of 200 to 250°C and salinities of 22 to 29 weight per cent NaCl for quartz from footwall albitites at Sullivan. Gardner and Hutcheon (1985) studied fluid inclusions from gangue minerals in cross cutting mineralization at the Jason deposit. They found the average temperature to be 276°C and average salinity 9.4 weight per cent NaCl. A brine of this temperature and moderate salinity would be quite buoyant and would rise as a plume above the site of exhalation.

Strontium isotope studies provide useful information on the source and nature of mineralizing fluids. Turner (1990) determined strontium isotope ratios of carbonate and barite samples from Jason and concluded barite may have precipitated from a stable brine ponded near the Jason fault.

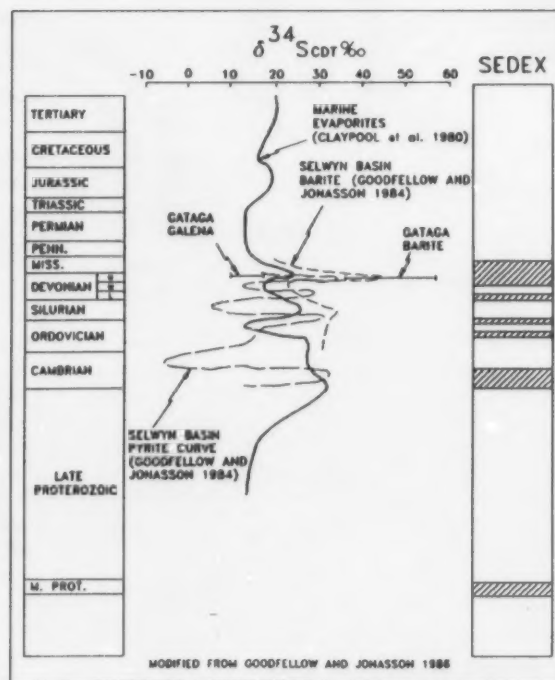


Figure 3-26. Sulphur isotope curves for barite and sulphide, Selwyn Basin and Kechika Trough. Modified from Goodfellow and Jonasson, (1986b). Gataga data from Lowey, 1984.

Pyrobitumen is common both in ancient sedimentary exhalative deposits, particularly in coarse-grained epigenetic veins and in modern submarine exhalative systems such as Guaymas Basin (Simoneit, 1986). The presence of pyrobitumen is probably due to cracking of detrital organic material in host sediments that have come in contact with heated brines (Simoneit, 1986).

TECTONIC CONTROLS

The formation of sedimentary-exhalative deposits is typically accompanied by synsedimentary faulting as indicated by rapid facies changes, sudden appearance of intraformational slump breccias, conglomerates and coarse-clastic turbidites, rapid thickening of sedimentary units and local submarine volcanic activity. During basinal subsidence the crust is attenuated and fault blocks are tilted along listric normal faults (Bond and Kominz, 1984; Coward, 1986). These faults probably provided channelways for the release of heated basinal brines trapped in permeable reservoirs or aquifers within the sedimentary succession. Upon exhalation, these brines accumulate as dense pools in submarine depressions such as linear, half-graben basins and troughs. Sulphide and barite is precipitated in response to the physiochemical conditions present (Figure 3-27).

Rifting and basinal subsidence often coincide with extensive periods of starved-basin sedimentation, stagnation of the water column and shallow water carbonate build-up. These relationships are not restricted to the host basin but are recognized worldwide. This suggests that periods of ocean stagnation and basinal subsidence, which are probably related to global tectonic processes, are important in formation of sedimentary-exhalative deposits (Goodfellow, 1987).

DEPOSIT MORPHOLOGY

The geometry and ore textures of sedimentary-exhalative deposits vary from massive, thick, coarse-grained lenses to extensive fine-grained laminations. These variations have been attributed to the temperature and density of the exhaled brines using the model developed by Sato (1972). In this model, dense, low temperature brines would tend to hug the seafloor and accumulate in depressions. Sulphide and or barite would precipitate periodically from these brines in response to changing physiochemical conditions. This would produce finely interlaminated sediment, sulphide and barite, a very common type of mineralization in sedimentary-exhalative deposits formed in anoxic basins (Jonasson and Goodfellow, 1986). On the other hand, hydrothermal fluid buoyant in the ambient water column might only precipitate sulphide at the vent as sulphides precipitated in the water column are widely dispersed. The result is thick sulphide mounds similar to those found at mid-ocean spreading centers. Such deposits would also

tend to be more copper rich if the fluids were higher temperature. Well-developed footwall alteration and stringer zones may develop if boiling takes place prior to fluid discharge (Large, 1983). Early sulphide and or barite phases might be replaced by continued circulation of fluids through the mound.

DISCUSSION

Formation of sedimentary-exhalative deposits occurred during specific time periods in the earth's history. This implies formation of these deposits is related to some geologic process that operated on a global scale. The almost universal association of these deposits with periods of rifting within the host sedimentary basin suggests periods of crustal attenuation were responsible. This rifting resulted in the formation of restricted second and third order basins with stagnant water columns that were favourable sites for the ponding of exhaled brines and subsequent formation of sulphide and barite beds on the seafloor.

The absence of major sedimentary-exhalative deposits in rocks younger than mid-Paleozoic has been noted by Turner (1988). Goodfellow (1987) suggests a stratified water column with sulphidic and anoxic bottom waters is a prerequisite for formation of sedimentary-exhalative deposits. Stable intracratonic or marginal basins are the most likely to produce these conditions. Perhaps the absence of such basins in Mesozoic and Cenozoic time explains why there are few sedimentary-exhalative massive sulphide and barite deposits of this age. During this time the oceans of the world may have been too well ventilated to produce long periods of anoxic stagnant marine conditions (Berry and Wilde, 1978).

EXPLORATION GUIDELINES

Major sedimentary-exhalative deposits are restricted to intracratonic basins and miogeoclinal older than mid-Paleozoic. As we have discussed, this type of deposit formed at certain time periods in the evolution of the earth's crust and our next challenge is to outline the extent of rocks of appropriate age. Good geologic mapping and paleontological studies are critical to this task. Next, having defined belts of appropriate age, we need to focus on favourable lithologies that might indicate a rifted, anoxic basin environment, for example, highly reduced carbonaceous siliceous shales, cherts and pelagic limestones. The occurrences of laminae and disseminations of pyrite and/or barite in these rocks would be a favourable indicator of exhalative activity within the basin.

Sedimentary-exhalative deposits are often associated with rifting and subsidence within the host basin. Evidence for such tectonic activity would include rapid facies changes, anomalous thickening of sediments, sudden appearance of intraformational breccias and conglomerates in starved-basin sediments and submarine volcanic rocks. Sedimentary-

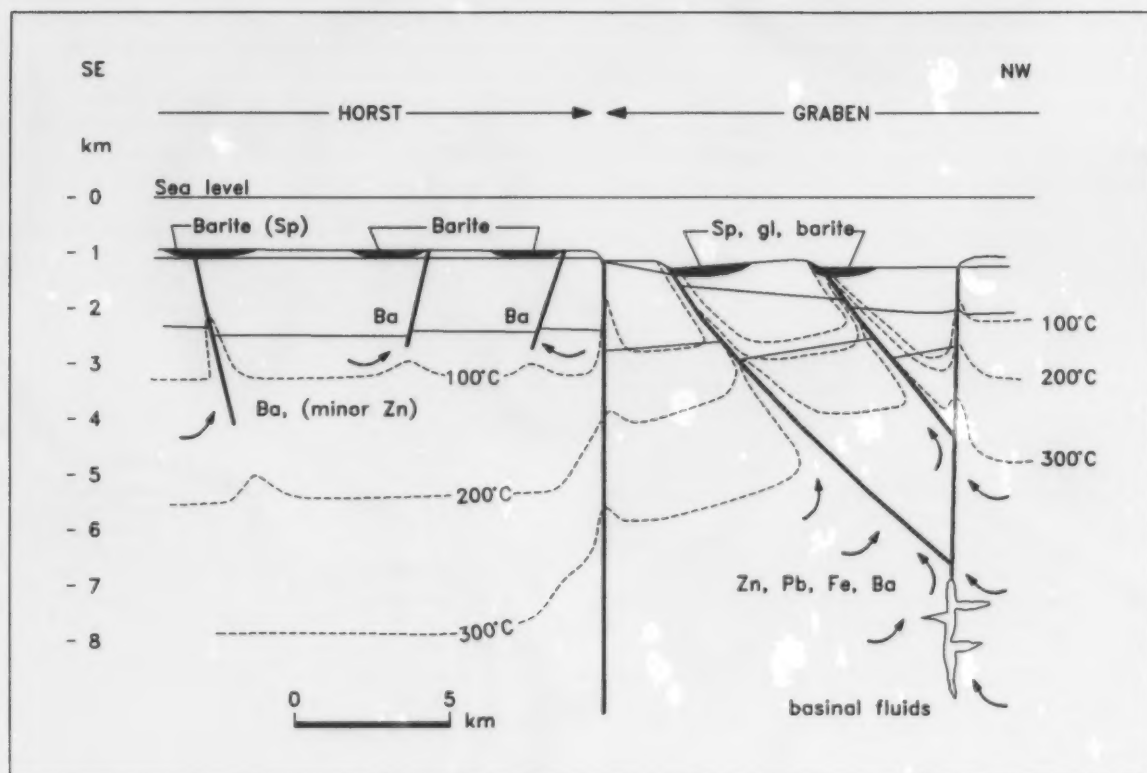


Figure 3-27. Hydrological model for formation of sedimentary exhalative deposits in the Macmillan Pass district. From Turner and Einaudi, 1986.

exhalative deposits, for example those of the Gataga district, are often located at or near the transition from anoxic starved-basin sedimentation as represented by carbonaceous cherty argillites to open marine turbidite deposition as represented by silty shale and siltstone and this transition may represent a favourable target.

Perhaps one of the best indicators of a favourable tectonic setting is the occurrence of a major fault zone. Compression of a rifted continental margin sequence, especially where half grabens have developed as a result of listric normal faulting, would naturally result in fault movement along existing crustal breaks. Today's major thrust faults may be reactivations of ancient continental margin rifts that were important in the localization of sedimentary-exhalative deposits. A good example of the importance of this relationship might be the deposits of the Gataga district, all of which are found in close proximity to major thrust faults (MacIntyre, 1983; MacIntyre, in press).

The recent discovery of a volcanogenic massive sulphide deposit, the Marg, along the inner to outer miogeocline transition zone in northern Selwyn Basin suggests that this tectonostratigraphic setting

should be more extensively explored. Large crustal breaks probably control this facies boundary, an extremely favourable environment for the formation of stratiform mineral deposits.

Ancestral North America and related terranes contain all the major sedimentary exhalative deposits known in the Canadian Cordillera. Another terrane with potential for this class of deposit is the Alexander Terrane. This terrane may be a displaced fragment of the continental margin that has been moved northward to its present position along the northern coast of British Columbia and Alaska. Thick sections of Paleozoic basinal and platformal sedimentary rocks that are lithologically and stratigraphically similar to miogeoclinal rocks of ancestral North America characterize this terrane. Some bedded barite deposits are known in southeast Alaska but overall the Paleozoic rocks have not been extensively explored for sedimentary-exhalative base metal deposits.

CONCLUSIONS

The Canadian Cordillera is well endowed with sedimentary-exhalative massive sulphide deposits.

In addition to the deposits of Middle Proterozoic and Devono-Mississippian age found world wide there are also important Early Cambrian and Early Silurian deposits. Favourable host rocks occur within Ancestral North America and the related Kootenay, Cassiar and Monashee terranes. Paleozoic rocks of the Alexander Terrane, a possible displaced fragment of the continental margin may have considerable potential for major sedimentary-exhalative deposits. Given the size and proven economic attractiveness of the sedimentary exhalative deposit type and the large number of deposits and occurrences already known, the Canadian Cordillera may be the best hunting ground in the world for this class of deposit.

ACKNOWLEDGMENTS

The author would like to acknowledge the many researchers who have contributed so much to the understanding of sedimentary-exhalative deposits. Most of the illustrations used in this chapter are derived from these sources. The reader is encouraged to consult the references cited for more detail on the deposits, districts and genetic models mentioned in this report. The author also thanks John Newell and Brian Grant for editing the original manuscript and Pat Desjardins, John Armitage and Pierino Chicorelli for drafting the final figures. The author gratefully acknowledges Bob Turner of the Geological Survey of Canada for reviewing the final manuscript.

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CARBONATE-HOSTED LEAD-ZINC ($\pm$ SILVER, GOLD) DEPOSITS OF BRITISH COLUMBIA

by JoAnne L. Nelson

INTRODUCTION

This paper deals with metallic and related deposits that are hosted by carbonate rocks. Skarns are excluded because they form the basis of a separate paper (Ray, this volume). Other than skarns, metallic deposits in carbonates can be divided into three major genetic categories. Excellent examples of each are found in British Columbia; they are,

- Syngenetic, Kootenay Arc type (Reeves MacDonald) and Shuswap deposits (Cottonbelt).

- Low-temperature epigenetic, Mississippi Valley type (Robb Lake).

- High-temperature epigenetic, manto-type (Midway).

Although thick and continuous carbonate horizons of Permian and Triassic age are present in all of the major suspect terranes in British Columbia, known metallic deposits are concentrated almost exclusively in early Paleozoic miogeoclinal carbonates, as shown on Figure 4-1. These include Lower

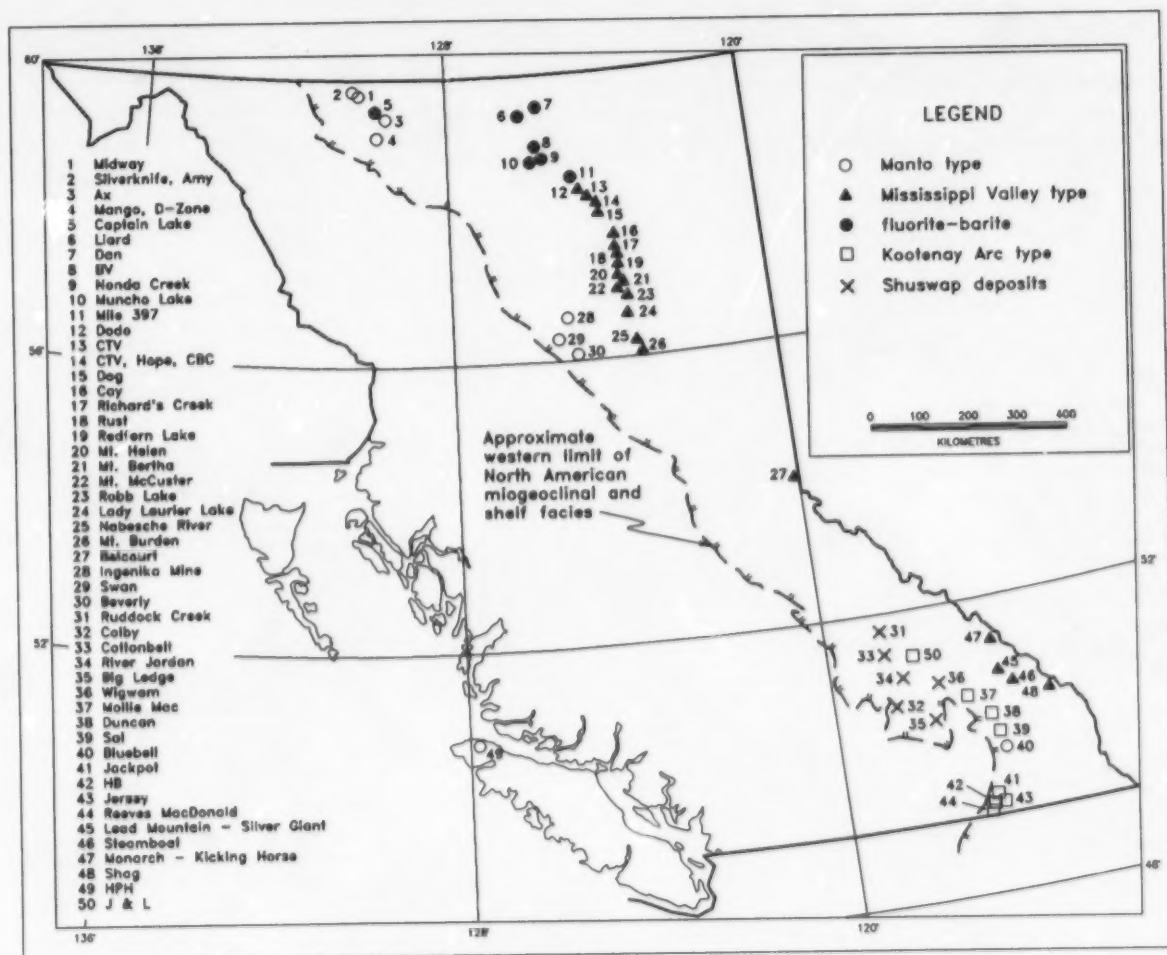


Figure 4-1. Locations of carbonate-hosted mineral deposits in British Columbia, excluding skarns. Deposits are detailed in Table 4-2.

Cambrian, Middle Cambrian, Siluro-Devonian and Middle Devonian units.

The three types of deposits overlap in their preferred hosts, but because each type has a unique genesis, each one requires different details of local geology such as facies changes, growth faults, karsting episodes or cryptic intrusions. These details provide clear exploration parameters. Further, each one of the three types has a different typical metal content and size potential, shown in Table 4-1. Worldwide, Mississippi Valley deposits are most common and generally the largest, although the 70 million tonne Navan body in Ireland with 12 per cent combined lead-zinc (Mills *et al.*, 1987) is a possible analogue of the Kootenay Arc deposits. Mantos tend to be small but rich in precious metals: where Mississippi Valley ores rarely contain more than 30 grams per tonne silver, manto ores commonly contain hundreds of grams; and at least one, the Ketza River deposit in Yukon (Carne, 1988), was mined for gold.

THE MODELS

KOOTENAY ARC-TYPE DEPOSITS

The Kootenay Arc is located in southeastern British Columbia near Kootenay Lake. It is a northerly

trending arcuate belt, concave to the west, of thrust-imblicated Proterozoic to Early Mesozoic miogeoclinal to basinal strata. Lower Paleozoic stratigraphy in the Kootenay Arc differs markedly from sections in the Rockies, in that carbonate intervals are much thinner and lower Paleozoic basinal shales and siliciclastics with interbedded volcanic rocks, now represented by the Lardeau Group, were deposited over a long period of time. The Kootenay Arc strata have been interpreted as an autochthonous North American off-shelf facies subject to repeated rifting events (Thompson *et al.*, 1987; Devlin, 1989). The massive carbonate Lower Cambrian Badshot Formation forms part of this sequence, lying above Proterozoic to Lower Cambrian siliciclastics and below the Lardeau Group.

The Badshot limestone and its equivalents, such as the Reeves limestone near Salmon, host numerous massive sulphide deposits. Some, particularly the small silver-rich occurrences, are of epigenetic origin. Most of the largest deposits, many of which have been mined, show a distinct syngenetic character (Table 4-2). These include the Reeves MacDonald, HB, Jersey and Duncan Lake deposits (Fyles and Hewlett, 1959; Höy, 1982). In morphology, these deposits are stratiform as well as strata-bound. As shown in Figure 4-2, the Reeves ore zone was folded, together with its enclosing limestones

TABLE 4-1

Characteristics of Mississippi Valley, Kootenay Arc and Manto-type Massive Sulfides in Carbonates

Tectonic Setting	Host Ages	Form, Mode of Origin	Commodities; Tonnage & Grade	Mineralogy	Exploration Parameters
(1) Mississippi Valley Type					
North America; near carbonate-to-shale transitions or stable platform (Pine Point) or in deformed belt (Robb Lake)	Cambrian Silurian Devonian	Tabular, tube-like, prisms. Open-space to replacement. Deposited from low-temperature basinal brines.	Pb, Zn, (Ga-Ge) Robb Lake: 5.5 mt 7.3% Pb-Zn	galena, sphalerite, barite, fluorite	- facies boundaries - brecciation - paleo-karst - dolomitization
(2) Kootenay Arc Type					
Kootenay Terrane (North American continental edge)	Early Cambrian	Tabular, irregular, disseminated. Characteristically as bedded sulfides, also laminae in carbonates, sulfide-matrix breccia; some cross-cutting. Syngenetic with feeders.	Pb, Zn, (Ag) Jersey: 7.68 mt 1.65% Pb, 3.49% Zn, 3.08 g/t Ag	pyrite, sphalerite, galena	- brecciation - dolomitization - growth faults
(3) Manto Type					
Cassiar Terrane and potentially ancestral North America.	Early Cambrian Middle Devonian	Irregular: tabular, wormlike, tubelike replacement bodies related to small felsic intrusions - generally A-type, anorogenic granites.	Ag, Pb, Zn; Au Midway: 1.2 mt 410 g/t Ag, 7% Pb, 9.6% Zn	galena, sphalerite, pyrrhotite, tetrahedrite, arsenopyrite, lead-tin sulfosalts, pyrrargyrite, barite, quartz, gypsum	- high-angle faults (at Midway 2nd order to transcurent faults.) - evidence of nearby subsurface or small intrusions

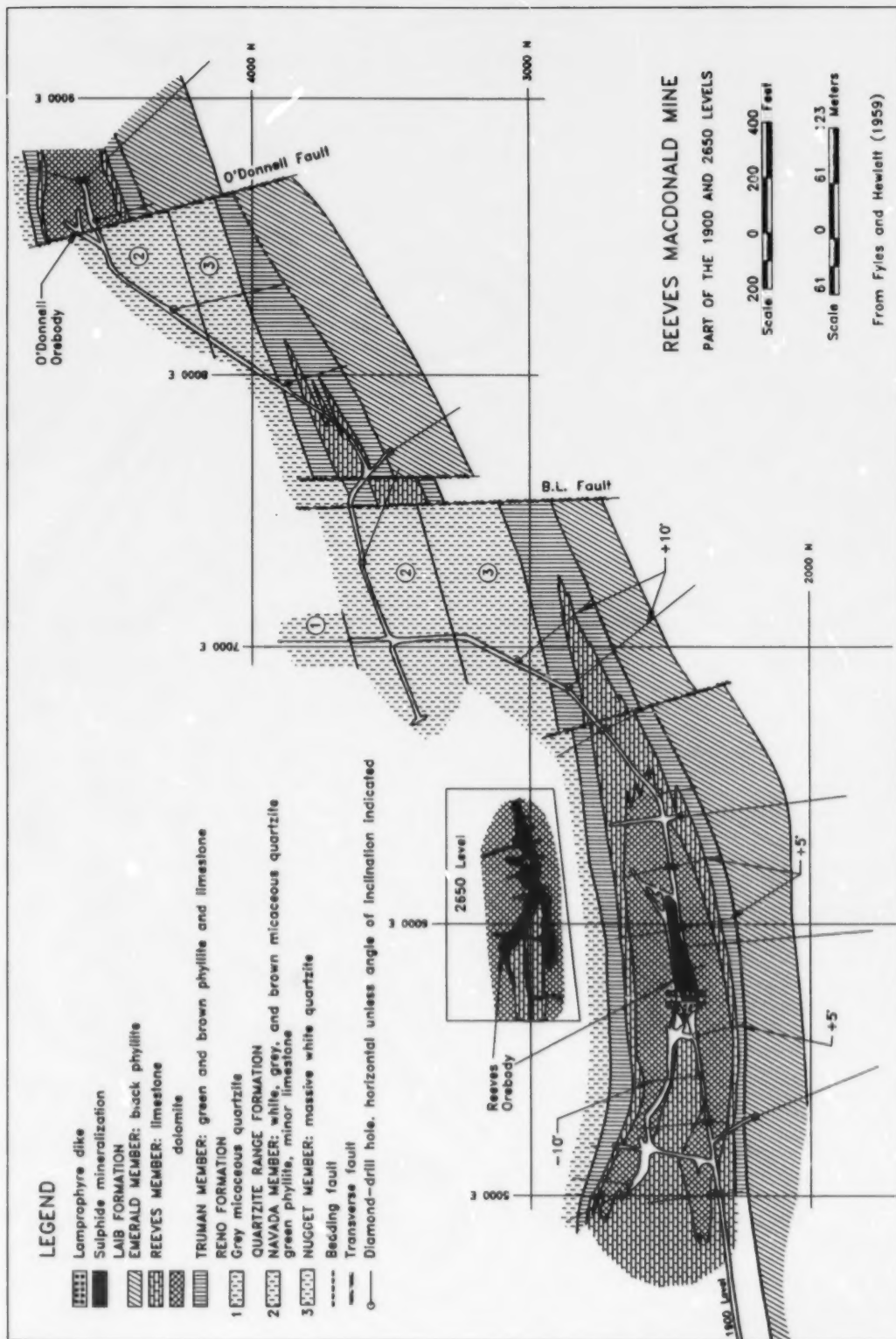


Figure 4.2. Cross section of the Reeves Macdonald orebody, Kootenay Arc (from Fyles and Hewlett, 1959).

TABLE 4-2

Carbonate-hosted Mineral Deposits in British Columbia

Name	MINFILE No.	UTM coord	Host formation	Tonnage/grade and Status	Deposit Type and age	Mineralogy
(1) Kootenay Arc-type Deposits						
Wigwam	82KNW 068	5636707N 431992E	Badshot, Lower Cambrian	occurrence	replacement	pyrrhotite, pyrite, fluorite, sphalerite, galena
Mollie Mac	82KNW 036	5615366N 477867E	Badshot, Lower Cambrian	occurrence	replacement	siderite, galena
Duncan	82KSE 19-23	5570659N 506173E	Badshot, Lower Cambrian	occurrence	stratiform: bands, lenses, layers veins in dolomite	galena sphalerite, pyrite
Sal	82KSE 015, 15-17	5553806N 512267E	Badshot, Lower Cambrian	occurrence	banded	pyrite, galena, sphalerite
Jackpot	82FSW 012 13, 255, 256	5454052N 488636E	Reeves Ls., Lower Cambrian	0.94 Mt, 4.68% Pb-Zn	well-banded layer- parallel lenses; superimposed skarn	pyrite, sphalerite, pyrrhotite, galena, scheelite, chalcopyrite
HB	82FSW 004	5444177N 485516E	Reeves Ls., Lower Cambrian	6.45 Mt, 0.77% Pb 4.1% Zn, 4.8 g/t Ag (production)	well-banded layer- parallel lenses	pyrite, sphalerite, pyrrhotite, galena
Jersey, Emerald- Tungsten	82FSW 009 10	5438222N 483939E	Reeves Ls., Lower Cambrian	7.68 Mt, 1.65% Pb, 3.49% Zn, 3.08 g/t Ag, .23% WO ₃ (production)	well-banded layer- parallel lenses; superimposed W-skarn mineralization	pyrite, sphalerite, galena, pyrrhotite, scheelite
Reeves Mac- Donald	82FSW 26-28	5430013N 474330E	Reeves Ls., Lower Cambrian	5.8 Mt, 0.98% Pb, 3.42% Zn, 3.4 g/t Ag, tr. Cd, Ga, Ge (production)	well-banded layer- parallel lenses	pyrite, sphalerite, galena
(2) Stratabound, Stratiform Deposits in Mixed Carbonate-Clastic Settings						
J&L		5681000N 421500E	Hamill Gp., Lower Cambrian	4.77 Mt, 7.2 g/t Au 72 g/t Ag, 4.3% Zn, 2.7% Pb	lenses and laminae in limestone and quartz- sericite schist	pyrite, arsenopyrite, sphalerite, galena
Cottonbelt	082M 086	5700916N 373369E	Shuswap Complex Lower Cambrian?	725 760 t, 6% Pb, 5% Zn, 60 g/t Ag	stratabound layers	galena, sphalerite, magnetite, pyrrhotite
River Jordan	082M 001	5664453N 401247E	Shuswap Complex, age unknown	2.6 Mt, 5.6% Zn, 5.1% Pb, 35 g/t Ag	stratabound layer, lenses in calcsilicate gneiss.	pyrrhotite, pyrite, galena, sphalerite, barite, fluorite
Big Ledge	82LSE 012	5591753N 425491E	Shuswap Complex, age unknown	occurrence	bands, lenses and disseminations in schist with calcareous lenses.	sphalerite, galena, chalcopyrite, pyrrhotite, pyrite
Ruddock Creek	082M 083	5736930N 367171E	Selkirk alloch- thon, age unknown (Windermere?)	occurrence	stratabound layers, in schist, calc- silicate gneiss, marble	sphalerite, pyrrhotite, galena, pyrite, chalcopyrite, fluorite, barite
(3) Mississippi Valley-type Deposits						
Robb Lake	094B 005	6310177N 455372E	Stone, Siluro-Devonian	5.5 Mt, 7.3% Pb + Zn	replacement in breccias	sphalerite, galena, pyrite

Name	MINFILE No.	UTM coord	Host formation	Tonnage/grade and Status	Deposit Type and age	Mineralogy
Lady Laurier Lake	094B 014 15	6285770N 46232E	Dunedin, Stone Nonda, Siluro-Devonian	occurrence	replacement in tectonic? breccia	sphalerite, galena
Nabesche R., WL, Nabe, Dev, Zrr, Cyn Wind	094B 009 10,11, 17,19	6240629N 474737E	Dunedin, Stone, Pine Point, Slave Point Siluro-Devonian	occurrence	replacement in dolomite breccias; veinlets in Besa River shale	sphalerite, galena
Mt. Burden, Poco	094B 007 8	6227078N 476208W	Stone Siluro-Devonian	occurrence	replacement in dolomite solution breccia	smithsonite, sphalerite, galena, quartz
Dodo	094K 058	6485169N 411508E	Dunedin, Middle Devonian	occurrence	pods (replacement).	galena, barite
CTV	094K 059 60,61	6475183N 418296E	Dunedin, Stone, Siluro-Devonian	occurrence	sphalerite in pod at and near Stone-Dunedin contact	sphalerite, barite, galena, fluorite
CTV, Hope, CBC	094K 062 63,64	6466203N 421722E	Dunedin, Middle Devonian	occurrence	pods, lenses (replacement) at base of Dunedin	galena, barite fluorite, pyrite sphalerite
Dog	094K 065	6446915N 430856E	Dunedin, Middle Devonian	occurrence	in brecciated limestone	sphalerite, galena
Cay	094G 017	6404394N 444095E	Dunedin, Middle Devonian	up to 6280 ppm Ge in sphalerite	pods	sphalerite, galena
Richards Cr., Faith, Ric	094G 006 10	6384391N 441327E	Stone, Dunedin, Siluro-Devonian	occurrence	disseminated, in pods	galena, barite, sphalerite quartz
Rust	094G 011	6374514 444281E	Dunedin, Middle Devonian	occurrence	veins	sphalerite, galena
Redfern Lake, Egg, Foo, Kei, Be, Besa	094G 002 9,12 16,18 019	6358687N 448375E	Dunedin, Besa River, Middle-Upper Devonian	occurrences	pods, disseminations barite-fluorite veins	sphalerite, galena, barite fluorite
Mt. Helen, Tri, Lynda, Boot, Heel	094G 007 008,13	6345708N 447608E	Dunedin, Stone, Siluro-Devonian	occurrences	in barite-filled breccia and solution-collapse breccias	sphalerite, galena, barite chalcocopyrite
Mt. Bertha, June	094G 004	6340785N 456003E	Dunedin, Middle Devonian	occurrences	veins, pods	galena, barite sphalerite
Mt. McCusker, Neil Jr., Lad	094G 005 14,15	6328063N 448999E	Dunedin, Pine Point, Middle Devonian	occurrences	with dolomite in thrust breccia	sphalerite, galena
Silver Giant	82KNE 018,	5642877N 536537E	Jubilee, Middle Cambrian	841,058 t, 3.5% Pb, 0.4% Zn, 23 g/t Ag (production)	replacement, cavity filling, veins	barite, galena, sphalerite, chalcocopyrite, bornite, stibnite?
Lead Mtn	82KNE 019	5642877N 536537E	Jubilee, Middle Cambrian	occurrence; 4.5% Pb, <1.2% Zn	cavity fillings, pods, disseminations	galena, sphalerite
Steamboat	82KNE 065	5615817N 557212E	Jubilee, Middle Cambrian	occurrence	pods, veins, cavity filling in silicified dolostone	galena, barite, smithsonite Cu-carbonate
Monarch, Kicking Horse	082N 020, 282	5697014N 538356E	Cathedral, Middle Cambrian	0.82 Mt, 5.63% Pb, 8.85% Zn, 31 g/t Ag	replacement, cavity filling in dolomitized, brecciated zone	galena, sphalerite
Shag	82JNE 002	5610508N 605284E	Cathedral, Middle Cambrian	occurrence	disseminations, veins	galena, sphalerite, pyrite
SOAB	82JSW 011	5551980N 636283E	Palliser, Devonian	occurrence	disseminated grains, cavity filling in algal-laminated dolostone	sphalerite, galena

Name	MINFILE No.	UTM coord	Host formation	Tonnage/grade and Status	Deposit Type and age	Mineralogy
(3A) Fluorite and/or Barite Deposits Spatially Associated with Mississippi Valley Type						
Liard Fluorite	094M 002 5-15	6593389N 665263E	Dunedin, Middle Devonian	many separate occurrences: Tam occurrence is 275 by 50-165 m (Pell and Fontaine 1989).	in solution-collapse breccia at top of Dunedin, below Besa R. shale: replacement, open-space filling	fluorite, barite, witherite, barytocalcite
Captain Lake Shawn barite	104P 049	6623054N 456907E	McDame Group, Middle Devonian	occurrence	barite in matrix of polymictic dolostone breccia	barite
BV, Snow	094N 002 3	6549480N 344875E	Chinchaga, Amica, mid-D. Middle Devonian	occurrences	bedded barite in dolomite; fluorite in fractures, replacement	barite, fluorite
Dan	094N 004 -7	6624719N 359285E	Dunedin, Middle Devonian	occurrences	blanket-shaped bodies at base of overlying Besa River shale	fluorite, barite, witherite, calcite
Nonda Creek	094K 001	6537400N 354465E	Dunedin?	estimated 500 000 short tons	vein at shale-limestone contact	barite
Muncho Lake	094K 038	6536250N 341266E	Dunedin?	occurrences	veins	fluorite, barite
Mile 397	094K 004	6505207N 396878E	Dunedin,	occurrence	irregular vein-like mass; replacement	barite, fluorite
(4) Mantos						
Midway	104O 038	6643875N 425070E	McDame Gp., Middle Devonian	1.2 Mt, 410 g/t Ag 7% Pb, 9.6% Zn	replacement in breccia at top of McDame, below Earn Gp. slates	galena, pyrite, sphalerite, arsenopyrite, pyrrhotite, marcasite, fribergite, Pb-Sn sulphosalts pyrrargyrite
Silverknife	104O 048	6645490N 423916E	Rosella, Lower Cambrian	occurrence; 511 g/t Ag, 3.7 g/t Au, 4.8% Zn, 12.25% Pb over 4.6 metres.	bedding-parallel replacement bodies	galena, sphalerite, pyrrargyrite, tetrahedrite, pyrite
Amy, Marbaco	104O 004	6644104N 416463E	Kechika Group, Cambro-Ordovician	72 438 t, 367 g/t Ag, 6% Zn, 2.84% Pb	bedding-parallel in unusually limy sections, near Cassiar	sphalerite, galena, pyrite, arsenopyrite, fribergite
Ax	104P 106	6598800N 471150E	Rosella, Lower Cambrian	occurrence	sulphide lenses in silicified zones	galena, sphalerite, chalcopyrite, bornite, chalcocite
Magno	104P 006	6568904N 452500E	Rosella, Lower Cambrian	200 487 t, 199 g/t Ag, 5.4% Pb.	sulphide replacement along fractures	magnetite, galena, pyrite, sphalerite, pyrrhotite, rhodochrosite
D Zone	104P 044 80,88	6570768N 452029	Rosella, Lower Cambrian	90 000 t, 70 g/t Ag, 3.3% Pb, 6.3% Zn (Middle D)	sulphide replacement pods in marble	magnetite, galena, sphalerite
Ingenika, Ferguson	094C 002 3	6284210N 367175E	Ingenika Gp., Lower Cambrian	average assay 210 g/t Ag, 15% Pb, 7.5% Zn over 2.4 m	replacements along bedding, quartz-siderite gangue	sphalerite, galena, pyrite, arsenopyrite, fribergite, chalcopyrite, pyrrargyrite
Swan	094C 073	6284516N 350182E	Ingenika Gp., Lower Cambrian	occurrence	disseminated sulphides in silicified top of carbonate	sphalerite, argentiferous galena, cerussite

Name	MINFILE No.	UTM coord	Host formation	Tonnage/grade and Status	Deposit Type and age	Mineralogy
Beverley, Weber, Davies, Gordon Regent	094C 023, 24,29-33,38-	6224848N 371830E	Ingenika Gp., Lower Cambrian	occurrence	disseminated, replacement sulphides	sphalerite, argentiferous galena, barite, pyrite
Bluebell	082FNE 043	5511923N 510323E	Badshot Ls., Lower Cambrian	4.82 Mt, 5.2% Pb, 6.3% Zn, 45 g/t Ag (production)	replacement, vein controlled by bedding, fractures, open-anticlinal culminations	pyrrhotite, Fe-sphalerite, galena, knebelite
H.P.H.	92L 069	5616380N 585180E	Quatsino Ls., Upper Triassic	occurrence	replacement sulphides in silicified limestone with nearby calcsilicate skarns	galena, sphalerite, chalcopyrite, magnetite, tetrahedrite, dyscrasite

during Jurassic (or possibly Mississippian; see Klepacki and Wheeler, 1985) tectonics. Sulphides within it range from massive beds to fine, continuous laminae that follow bedding in the host limestones; laminae are deformed into mesoscopic folds that mimic the large-scale structures. The sulphide laminae provide a strong argument for syngenetic origin. Within the more massive ore, breccia textures are common, composed of angular carbonate clasts floating in sulphide matrix. These textures have led some workers to infer an epigenetic, replacement origin for the deposits (Fyles and Hewlett, 1959; Muraro, 1962). Höy (1982) synthesizes the two models into a proximal-distal exhalative model. He ascribes the breccias to local subaerial weathering of carbonate buildups, followed by sulphide infilling and partial replacement in vent areas, while the laminated ore represents more distal sulphide precipitation out of brines as they mixed with seawater (Figure 4-3).

The Kootenay Arc deposits are somewhat analogous in their setting to the large carbonate-hosted lead-zinc orebodies in Ireland - Tynagh, Navan, Silvermines, and Gortdrum. The Irish deposits are

mostly hosted by mixed limestone-shale shallow-water sequences of Early Mississippian age. Tynagh, Silvermines and Gortdrum are close to synsedimentary faults. The ore textures indicate both syngenetic and epigenetic mineralization; much of the latter is inferred to have taken place during early diagenesis (Boast *et al.*, 1981). Except for the Navan ores, which contain sphalerite, galena, pyrite, barite and fluorite, ore mineralogy tends to be more complex than the Kootenay Arc deposits. Tynagh contains galena, sphalerite, arsenopyrite, tennantite, chalcopyrite, bornite and barite; Silvermines contains pyrite, sphalerite, galena with traces of chalcopyrite, tennantite, boulangerite, bournonite, jordanite and pyrrhotite. Average silver grades range from 20 to 90 grams per tonne.

Except for the shallow water depths involved, the Kootenay Arc model also resembles that described by Turner and Rhodes (1990) for the MacMillan Pass area in the Selwyn Basin, a large basinal reentrant into the North American margin in Yukon. At MacMillan Pass a single exhalative system encompasses mineralization of both epigenetic and syngenetic character. Fluids that fed the sedimentary-exhalative, stratabound sulphide deposits ascended along penecontemporaneous faults: evidence for this remains in sulphide-cemented breccias associated with local coarse-clastic deposits and slumps. Like the Kootenay Arc, the Selwyn Basin was affected by episodic rifting. Extensional tectonics - high heat-flow, abundant faults, second-order basins in which brines could pool - provided favourable conditions for economic sedex mineralization, whether shale-hosted or within carbonate rocks. Because of this necessary tectonic setting, Kootenay Arc-type deposits are not found in the Rockies or on the stable craton, but only along the outer continental margin. On a smaller scale, exploration should focus on evidence for local penecontemporaneous faulting - local unconformities, brecciation, slump deposits. In addition, the deposits are surrounded by extensive envelopes of secondary

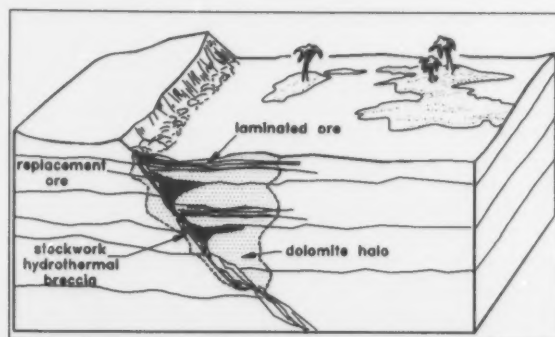


Figure 4-3. An integrated model for Kootenay Arc and Irish deposits.

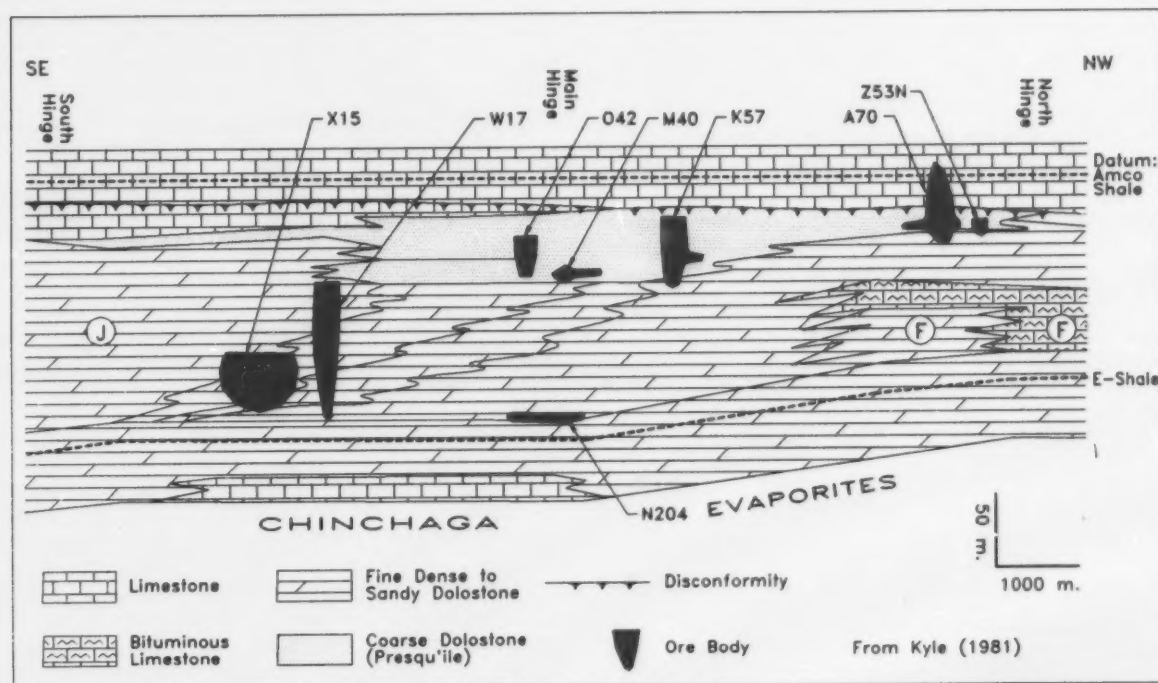
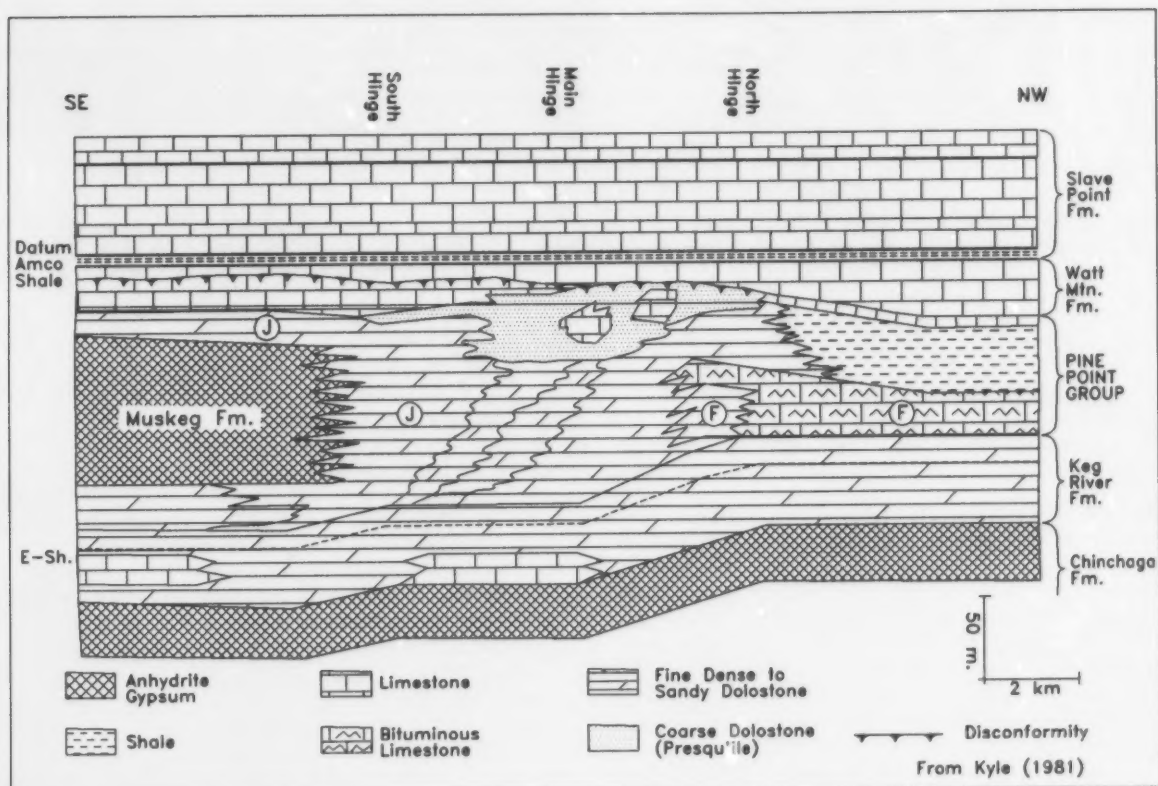


Figure 4-4. (a) Overall geometry of the Pine Point carbonate barrier. J facies= lagoonal, F facies= deep-water (from Kyle 1981). (b) Facies control of Pine Point orebodies. Note location of orebodies at contact of dolostone barrier complex with evaporites and within secondary coarse dolostone.

dolomite (c.f. Figure 4-2), which may be a useful prospecting tool.

The 4.77 million tonne J&L prospect at the northern end of the Kootenay Arc is a stratabound deposit that shows some resemblance to the other Kootenay Arc deposits, but also some unique features. It occurs in a strongly deformed, structurally complex mixed carbonate-siliciclastic package of probable Lower Cambrian strata (Höy, 1985). Mineralization is concentrated near the top of a limestone that Höy (personal communication, 1991) correlates with the Badshot limestone. Sulphides are interlayered and interlaminated both with the limestone and with structurally overlying quartz-sericite schist. Sulphides include pyrite, arsenopyrite, sphalerite and galena. Average grade is 7.2 grams per tonne gold, 72 grams per tonne silver, 4.3 per cent zinc, 4.5 per cent arsenic and 2.7 per cent lead, although the newly discovered Yellowjacket zone is a zinc-lead-silver lens, estimated to contain 910 000 tonnes grading 7.4 per cent zinc, 2.6 per cent lead and 55 grams per tonne silver, hosted entirely by limestone (Preto, 1991). The significant gold values and presence of arsenopyrite are anomalous in Kootenay Arc deposits, as is the presence of layered sulfides outside of the Badshot limestone. This deposit is interesting in that it represents a transition between a carbonate-hosted exhalite of the Kootenay Arc type and a clastic-hosted sedimentary exhalite.

Partially carbonate-hosted deposits in the Shuswap Complex include the Cottonbelt, River Jordan and Big Ledge occurrences. The Ruddock Creek showing occurs within the Selkirk allochthon above the Monashee décollement. All are hosted by mixed carbonate-siliciclastic sequences; the presence of carbonate lithologies may be irrelevant to their formation. Cottonbelt, for instance, is a thin (15 centimetres to 3 metres) but laterally very extensive (4 kilometre strike-length) lead-zinc-magnetite exhalite (Höy, 1987). It lies stratigraphically less than 100 metres above the Mount Grace carbonatite. These deposits are affiliated with sedex deposits in shale basins, and are intermediate between them and the Kootenay Arc type.

MISSISSIPPI VALLEY-TYPE DEPOSITS

Large lead-zinc ($\pm$ barite, fluorite) deposits in carbonate rocks are common in the eastern interior of the United States. This class also includes the Pine Point, Nanasivik and Polaris orebodies in Canada. In British Columbia it is represented by numerous deposits in the northwestern Rockies, most notably Robb Lake. Mississippi Valley-type deposits are irregular in shape, partly open-space filling and partly of replacement origin. A voluminous literature describes their characteristics and speculates on their origin. They tend to occur on stable platforms as opposed to continental margins and are not associated with igneous or local tectonic events (Anderson and MacQueen, 1982). Mississippi Valley

deposits favour facies fronts, for instance the Devonian Pine Point barrier complex that separates evaporites to the south from a shale basin to the north (Figure 4-4; Kyle, 1981). Generally, there is evidence of premineral and synmineral karsting including collapse breccias, lag sediments, overall deposit morphologies that include horizontal tubes and vertical collapse chimneys (Figure 4-5; Rhodes *et al.*, 1984). The development of open space by karsting is an important mechanism of ground preparation for these deposits. Dolomitization is an almost universal association: as a means of ground preparation, dolomitization of limestone produces a net volume decrease, which promotes the development of open space.

The ore fluids in Mississippi Valley deposits are modelled as far-travelled basinal brines, driven by basin dewatering (Jackson and Beales, 1967) or by the hydraulic head created by uplift of the basin margins (Garven, 1985; Leach and Rowan, 1986; see Figure 4-6). In either case, they represent major aquifers that penetrated to deep levels in the basin. Fluid inclusions show high salinities, greater than 15 per cent, and temperatures generally in the range 80 to 200°C, although some fluids at Pine Point range as low as 50°C (Table 4-2). These temperatures are very low compared to those associated with most other mineral deposits; on the other hand, given typical geothermal gradients in sedimentary basins in stable platform settings of 25 to 30°C, they imply very deep fluid circulation and/or abnormally high local heat flow (Anderson and MacQueen, 1982).

In British Columbia, a nearly linear belt of Mississippi Valley-type lead-zinc occurrences is hosted by Siluro-Devonian platform carbonates east and north of Williston Lake (Figure 4-1 and Table 4-2). Most notable of these is the Robb Lake deposit, with geological reserves of 5.5 million tonnes at an average grade of 7.3 per cent combined lead and zinc. The Cay occurrence contains significant gallium and germanium as trace constituents in sphalerite (Leighen *et al.*, 1989). In some areas, such as near Redfern Lake, fluorite and barite mineralization is spatially associated with sulphide occurrences and could be used as an exploration guide; although other fluorite and barite deposits are remote from any known lead-zinc showings, for instance the Liard fluorite. Fluorine and sulphate are expected constituents of fluids that have passed through evaporite horizons; such fluids have also been implicated in the formation of Mississippi Valley deposits, particularly as a source of sulphur (Beales and Jackson, 1968). The presence of pyrobitumen associated with the Robb Lake deposits suggests a tie to oilfield brines.

Although they occur within the deformed belt rather than a stable platform, this group of deposits conforms to the Mississippi Valley model in terms of morphology, mineralogy, textures, and stratigraphic setting. They occur within the Muncho-McConnell,

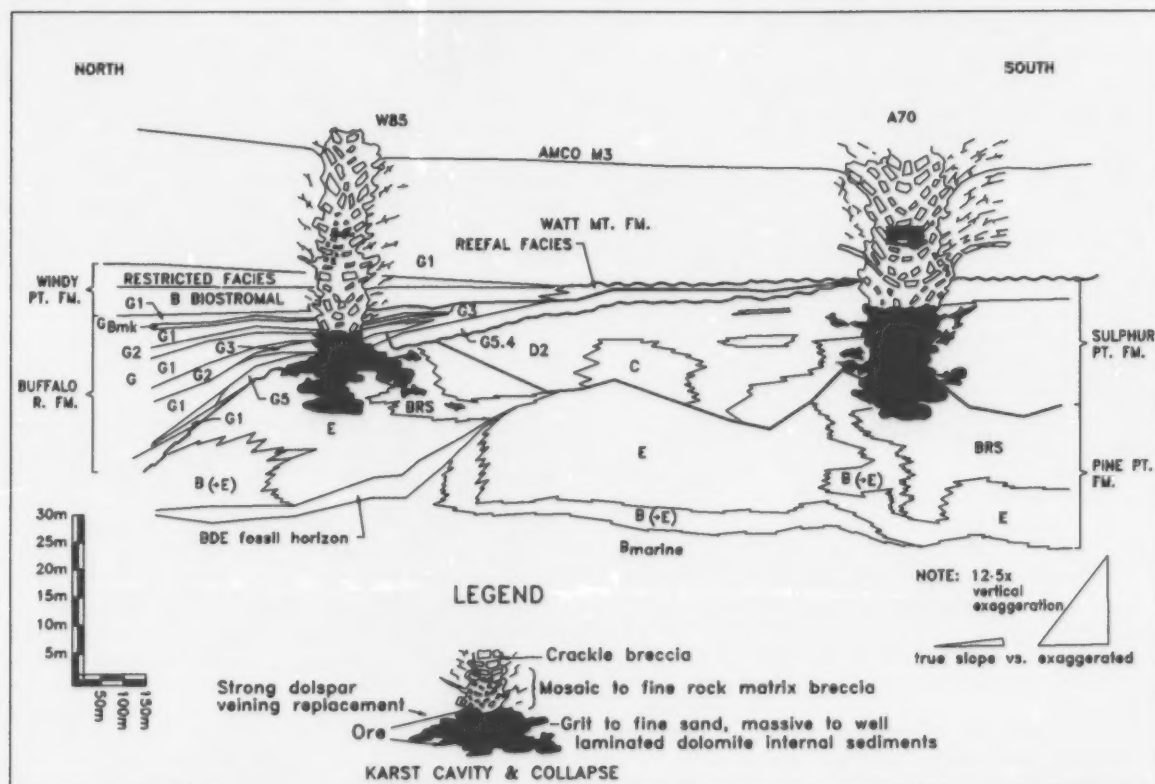


Figure 4-5. Karst control of Pine Point orebodies (from Rhodes et al., 1984).

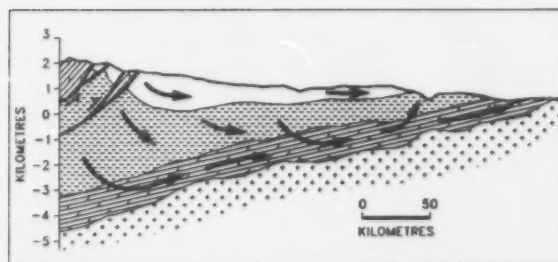


Figure 4-6. Basin-scale aquifer driven by topographic uplift at basin margin (from Garven, 1985). Fluid flow is driven by the hydraulic gradient created by a sloping water table.

Stone, Dunedin, Slave Point and Pine Point formations immediately east of the facies change to Besa River shales (Figure 4-7; MacQueen and Thompson, 1978). Robb Lake itself is hosted by Silurian dolostones, representing lagoonal to supratidal, sabkha-type deposition (Manns, 1981). This stratigraphic setting, though not identical, is analogous to that of Pine Point; in fact the northwesterly-trending Devonian facies front in northeastern British Columbia continues in the subsurface and becomes the Pine Point barrier.

Sulphides in the Robb Lake deposit occur mainly within the matrix of stratabound and crosscutting breccias, which are somewhat problematic in their mode of origin (MacQueen and Thompson, 1978; Manns, 1981). The role of karsting is not as clear as at Pine Point. Some of the other lead-zinc occurrences in the district are fracture fillings. The timing of sulphide emplacement is very poorly constrained. Manns (1981) considers it predates Laramide deformation, on the basis of rotated geopetal structures. If this is so, then the deposits in northeastern British Columbia formed prior to the tectonic uplift depicted by Garven (1985) (Figure 4-6). In order to integrate them into his basin-circulation model one would have to relate them to a very early and more westerly phase of Laramide deformation.

Farther south in British Columbia, the Siluro-Devonian carbonate facies front is largely obscured by strike-slip faulting, thrust tectonics and erosion. The Late Devonian Palliser Formation in the Rocky Mountains of southern British Columbia hosts several small stratabound lead-zinc showings, which consist mainly of disseminations in algal-laminated carbonate rock and may be syngenetic to early diagenetic in origin (Höy, 1982). Middle Cambrian limestones in the southern Rocky Mountains and in the Kootenay Arc near the British Columbia-

Washington border are correlatives of the highly productive Metaline limestone in northern Washington State (Mills, 1977). Höy (1982) links the Middle Cambrian deposits of southern British Columbia to the carbonate front.

MANTO-TYPE DEPOSITS

Manto deposits have long been recognized in Mexico (c.f. Prescott, 1926), but the widespread application of this important model to the Canadian Cordillera is a very recent phenomenon. In Spanish, a manto is defined as a cloak or cape. Manto-type deposits are irregular, sulphide replacement bodies in carbonate hosts that include true mantos and tubes along bedding but also cross-cutting chimneys (Figure 4-8; see also Prescott, 1926, MacDonald *et al.*, 1986, Beaty *et al.*, 1986). There is an implied genetic connection to an intrusive body as a source of fluids, which gives mantos many features that low-temperature Mississippi Valley-type deposits lack, such as complex mineralogy and high silver contents (Table 4-1). On the other hand, mantos are distinct from skarns in that they are massive sulphide bodies that may lack any trace of calcisilicate minerals; most known mantos have very distal rather than proximal relationships to intrusions. The igneous contribution to them is marked by the presence of tin and fluorine, and by relatively high temperatures of the ore fluids, although not so high as those that form skarns. Their silver-rich character makes them attractive exploration targets in spite of their small tonnages compared to Mississippi Valley deposits. One unusual oxidized manto deposit,

Ketza River in Yukon, has gold values typically in the 10 to 20 grams per tonne range.

Manto-type deposits are shaped very much like caves in limestone. Like caves, they are controlled by pre-existing open spaces and relatively soluble zones along bedding planes and fractures. Figure 4-9 shows the Cumbres orebody, part of the Ojuela mine in Mexico. It consists of mantos that follow bedding planes in an anticlinal core linked by steep, fracture-controlled chimneys. In cross-section the Cumbres orebody is worm-shaped, not tabular. The Midway deposit in the Cassiar Mountains of northern British Columbia is a classic manto deposit (Bradford, 1988). It forms a cluster of irregular, manto-shaped to tube-like replacement bodies in limestones near the top of the Middle Devonian McDame Group.

The Midway deposit is an excellent example of the character of manto deposits and the type of evidence that can be used to explore for them. It is located within the Cassiar Terrane, a sliver of the North American miogeocline west of the Tintina fault. Its host, the Upper McDame Group, is an extensive back-reef, lagoonal facies that is overlain by black shales at the base of the Devonian-Mississippian Earn Group. The base of the shale sequence forms an abrupt physical and chemical(?) barrier: the only mineralization above it is in a few very narrow veins. The deposit lies within the Tootsee River fault zone, a zone of anastomosing high-angle faults that may be

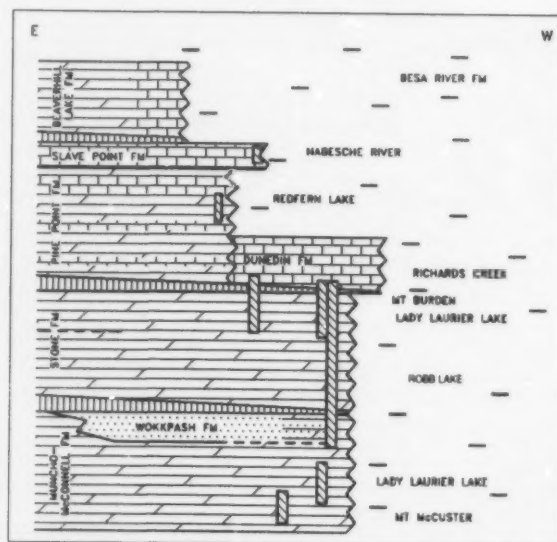


Figure 4-7. Control of Robb Lake and associated deposits by the carbonate to shale transition, shown in diagrammatic east-west cross section, looking south (from Macqueen and Thompson, 1978).

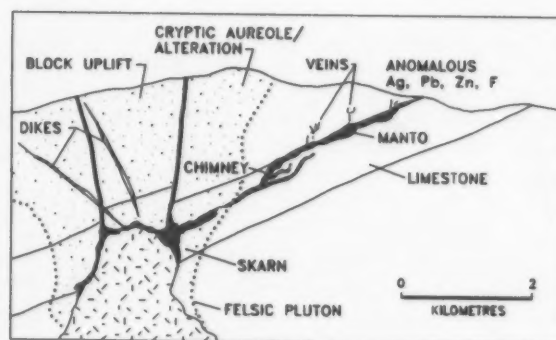


Figure 4-8. Generalized manto model.



Figure 4-9. Cross section of the Cumbres orebody (after Prescott, 1926).

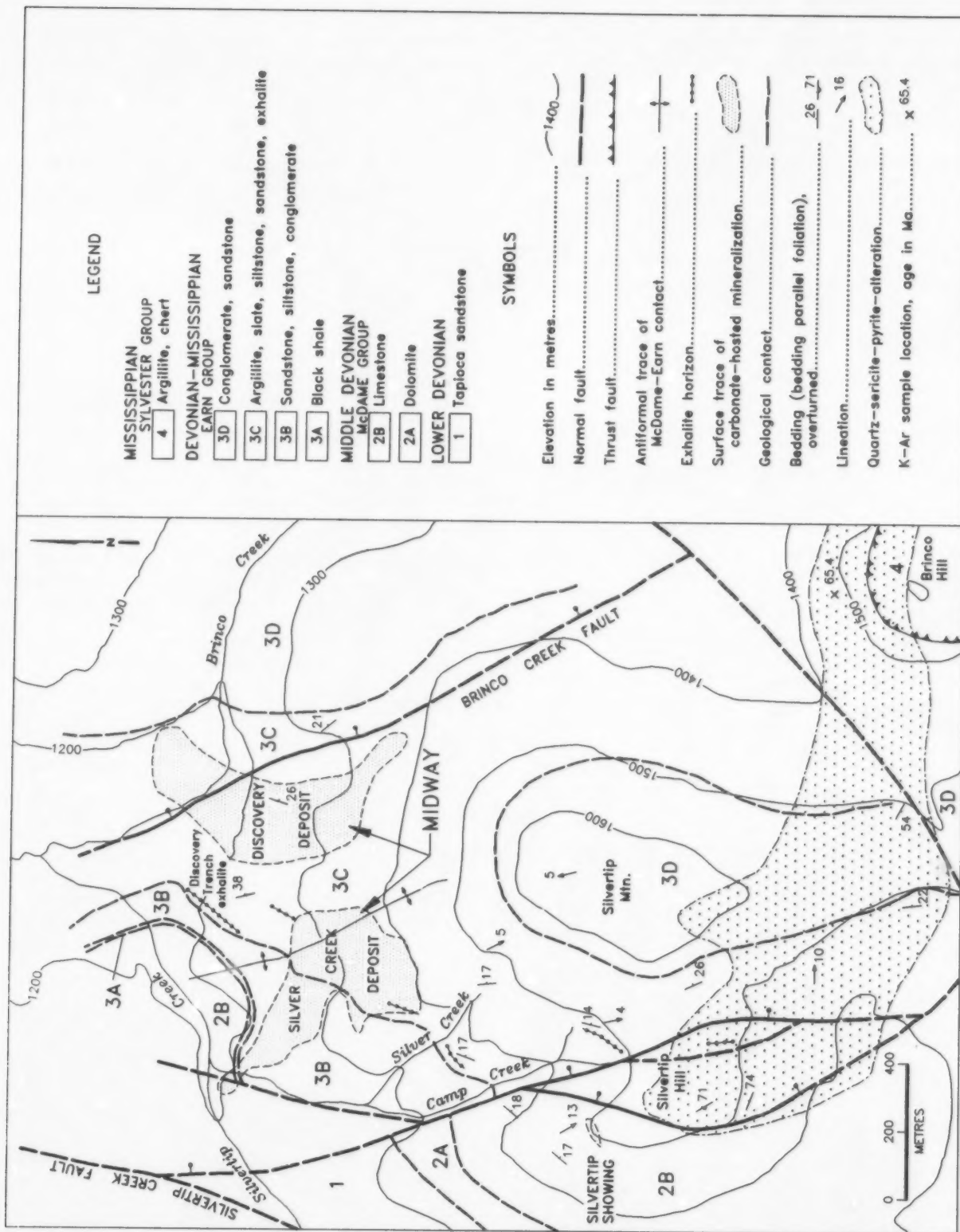


Figure 4-10. Map of the area surrounding the Midway deposit, showing subsurface ore zones, surface faults and alteration zones (from Bradford, 1988).

linked to the Kechika fault (Figure 4-10). This fault zone was probably a key control both on the emplacement of the intrusion, and for channelling hydrothermal fluids.

There is abundant indirect evidence for a buried intrusion that generated the mineralization at Midway. The ore itself shows a complex mineralogy, including pyrite, sphalerite, galena, pyrrhotite, fribergite, arsenopyrite, pyrargyrite, and tin and lead sulphosalts. Skarn minerals were identified in one of the deepest holes. Two zones of quartz-sericite alteration have affected the rocks lying stratigraphically and structurally above the deposit (Figure 4-10). Sericites from these zones give Late Cretaceous, 70 Ma K-Ar ages. The sericites have elevated fluorine contents (Bradford, 1988; D. Sinclair, personal communication, 1991). In the more easterly alteration zone, strongly altered quartz-biotite-porphyritic rhyolite dikes are also of Late Cretaceous age. A roughly circular, negative magnetic anomaly under Brinco Hill may be the signature of a felsic pluton in the subsurface, about 2 kilometres from the main deposit. Fluid inclusions from the Midway deposit are H_2O - CO_2 -salt solutions with main-stage homogenization temperatures in the 270 to 340°C range. Evidence of coexisting H_2O and CO_2 -rich fluids suggests that these represent the actual temperatures during mineralization (Bradford, 1988).

A wide variety of breccias at the Midway deposit attests to the complex history of ground preparation and multiphase mineralization. They can be classed as pre-ore, syn-ore and post-ore. Pre-ore breccias involve both McDame limestones and shales of the Earn Group that apparently collapsed into solution cavities at the top of the McDame during early karsting. Bedded karst sediments occur in places. Syn-ore breccias, located well within the McDame Group, contain clasts of both McDame and Earn lithologies as well as scattered sulphide clasts, in a matrix of sulphides, calcite and fine detritus. They show that mineralization was accompanied by the formation, or at least the enlargement, of solution cavities and ensuing collapse.

The Midway deposit was discovered by drilling in 1983, during a program that targeted sedex-type mineralization in the overlying Earn Group. The deposit is completely blind. It is an instructive exercise to turn back the clock and, knowing what we now know, try to rediscover Midway. The criteria are enumerated below in the order of decreasing scale.

Terrane scale: The necessary matrix is carbonate, with a likelihood of Cretaceous or Eocene intrusions and high-angle faulting. These criteria are met in the Cassiar Terrane, Kootenay Terrane and parts of ancestral North America within the deformed belt of the Cordillera. Likely carbonate hosts in these terranes are mostly of Early Cambrian and Siluro-

Devonian age. In the western Cordillera, skarn deposits may include massive sulfide manto facies.

Map scale (1:250 000): The McDame Group and also the carbonate strata of the Lower Cambrian Rosella Formation are well-exposed in the north-eastern corner of the Jennings River map sheet. The original Geological Survey of Canada map (Gabrielse, 1969) shows the major faults of the Tootsee River system. Within the fault array and only 1.5 kilometres from the Midway portal (Figure 4-10), the Silvertip occurrence, a small lead-zinc surface showing in the McDame limestone, was first explored in 1958.

Map-scale (1:50 000): Extensive gossans are associated with the quartz-sericite alteration zones in the Earn Group and Sylvester allochthon. They delineate an area of interest, heightened by regional stream geochemical anomalies in silver, lead, zinc and fluorine. Careful exploration reveals, in addition to syngenetic occurrences in the Earn, a few small veins that carry galena. Given the tendency of large mantos to end abruptly against non-limestone hosts, such veins should be very exciting indeed to the explorationist. In the case of Midway, a hole collared at one of these veins would intersect the core of the deposit.

Figure 4-10 summarizes the manto model and illustrates surface indications of a manto system at depth. Known manto deposits are at present a rarity in British Columbia. This may be in part a result of nonrecognition. The old Ingenika lead-zinc-silver mine in the Aiken Lake map area (Figure 4-1, Table 4-1) exploited a series of bedding-parallel replacement sulphide bodies in Lower Cambrian limestone. Ore mineralogy includes quartz, siderite, arsenopyrite, pyrite, pyrrhotite, sphalerite, chalcopyrite, fribergite and pyrargyrite (Roots, 1954). The Lower Cambrian carbonates in the Aiken Lake map area host a number of smaller occurrences that deserve further exploration.

The Lower Cambrian Badshot limestone in the Kootenay Arc is another likely setting for manto deposits, given the abundance of Jurassic to Cretaceous plutons in the area and the abundance of silver-lead-zinc veins. The Bluebell deposit (Figure 4-1, Table 4-2) is an irregular replacement body controlled by bedding, by the external contacts of the Badshot limestone, by anticlinal culminations, lamprophyre and pegmatite dikes and joints (Shannon, 1970; Figure 4-11). Its lead-isotopic character is identical to that of veins in the Jurassic Nelson batholith (Logan *et al.*, 1987) and high fluid inclusion homogenization temperatures, in excess of 450°C (Ohmoto and Rye, 1970). The average silver content of Bluebell ore, at 60 grams per tonne, is midway between the low-silver syngenetic and Mississippi Valley deposits and the silver-rich mantos. Ore mineralogy includes pyrrhotite, iron-rich sphalerite, galena, knebelite (Fe-Mn olivine), quartz and calcite.

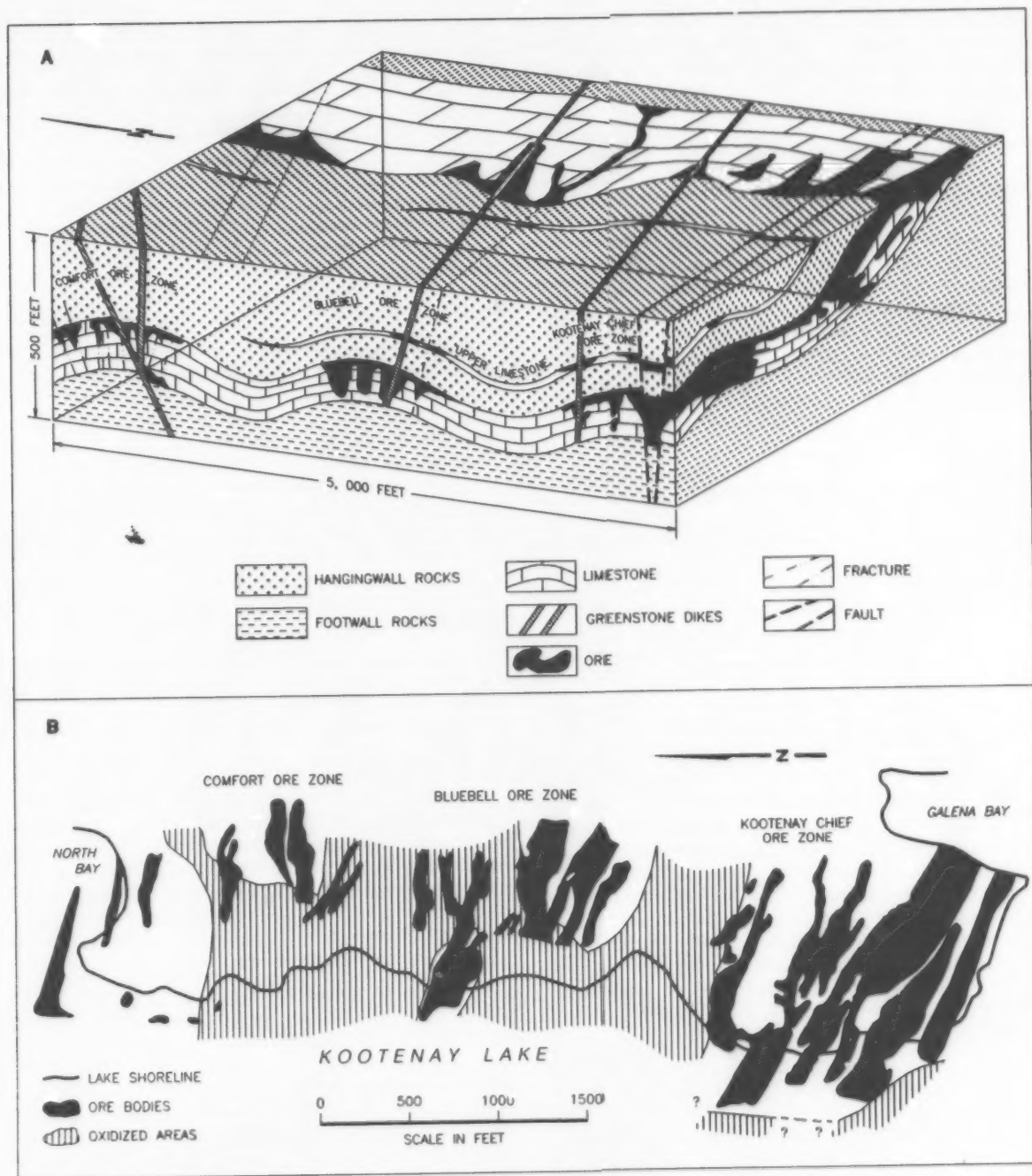


Figure 4-11. Outlines of the Bluebell ore zones, showing stratigraphic and tectonic controls (from Shannon, 1970).

The H.P.H. occurrence on Vancouver Island is a series of small lead-zinc-silver mantos that replace limestone of the Upper Triassic Quatsino Formation (Gunning, 1932). High-grade chip samples of galena-sphalerite typically contain thousands of grams per tonne silver. Granodiorite and skarn occur near the sulphide bodies, but silicification is the only alteration directly associated with them.

LEAD ISOTOPIC SIGNATURES OF CARBONATE-HOSTED DEPOSITS

All rock systems contain uranium, lead and thorium. The radioactive decay of ^{238}U to ^{206}Pb , ^{235}U to ^{207}Pb and ^{232}Th to ^{208}Pb produces a regular and mathematically predictable increase in the ratios of these radiogenic lead isotopes to ordinary lead, ^{204}Pb , through time. Galena, however, contains virtually no uranium or thorium. Its lead isotopic composition is "frozen in" at the time of crystallization, and provides a sample of the lead in the ore fluid from which it grew. In the simplest case this composition reflects the age and Pb:U:Th ratio of the source terrane and the age of the deposit. The sedex deposits of the Canadian Cordillera fall in this category. Galena leads from Helikian to Mississippian-aged stratabound ores define single lines in terms of $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plots. These are the "shale curves" (Figure 4-12), lead isotopic evolution curves described for the western edge of ancestral North America in a seminal paper by Godwin and Sinclair (1982). The existence of such well-defined local growth curves means that lead isotopic data from the eastern (ancestral North American) Cordillera can be interpreted with far greater precision than is attainable if only general crustal-evolution models are used. In terms of lead isotopic modelling, shale-hosted exhalite deposits are well-behaved, that is their isotopic ratios reflect the average ratios in the upper crustal reservoir at the time of their formation. Carbonate-hosted deposits range from well-behaved to erratic. Manto deposits in the Canadian Cordillera show the most easily explicable lead isotopic systems. Midway, for instance, plots on or near the youngest end of the shale curve: its lead is essentially a sample of upper crustal North American lead taken 70 Ma ago (Figure 4-12). Bluebell leads plot far below the shale curve in a population that includes veins in the Nelson batholith. This relatively unradiogenic, primitive lead probably reflects the isotopic character of the Nelson batholith itself.

The stratabound, apparently syngenetic Cottonbelt deposit in an undated carbonate in the Shuswap Complex has been assigned a Cambrian age by Höy and Godwin (1988) based on the similarity between its lead isotopic composition and that of Cambrian shale-hosted deposits. In contrast, the syngenetic Kootenay Arc deposits, which occur within well-dated Lower Cambrian limestone, show an anomalous signature.

Given that they are syngenetic in Lower Cambrian North American strata, their lead compositions ought to coincide with that of Lower Cambrian shale-hosted syngenetic deposits such as Faro; but instead they form a linear array spread along and near the shale curve in the Late Paleozoic to Early Mesozoic age range. Even more anomalous are the Robb Lake deposits, which form elongate linear arrays extending from near the "young" end of the shale curves toward the extremely radiogenic lead – the so-called "future lead" observed in many Mississippi Valley type deposits (Heyl *et al.*, 1974). These lead trends are too long to correspond to any realistic time interval; more problematic still, their ratios of, for instance, $^{206}\text{Pb}/^{207}\text{Pb}$ exceed those possible for any rock system at present, no matter how uranium rich. These isotopic ratios probably reflect nonequilibrium processes involved in leaching of lead by fluids at very low temperatures, in contrast with the representative lead samples seen in high-temperature mantos. Of the radiogenic isotopes ^{206}Pb shows the greatest enrichment, followed by ^{208}Pb and then ^{207}Pb . Identical patterns are observed in data from the Mississippi Valley deposits

TABLE 4-3

Fluid Inclusion, Lead and Sulphur-isotopic Comparisons

Fluid inclusion data	Pb-isotopic signature	Sulphur ($\delta^{34}\text{S}\%$)
(1) Manto Deposits		
Midway: $T_{\text{homog}} = 267\text{--}340^\circ\text{C}$ ($\text{H}_2\text{O-CO}_2$); Immiscible in part. 120–176°C (H_2O only). (Bradford, 1988)	Midway: cluster at/near shale curve in Late Cretaceous-Eocene age range	Midway: 7.8 (py) 7.5 (sl) 5.9 (gn) (Bradford, 1988)
Deer Trail: $T_{\text{homog}} = 250\text{--}300^\circ\text{C}$ ($\text{H}_2\text{O-CO}_2$); immiscible fluids observed. 0–22% NaCl equivalent (Beatty <i>et al.</i> , 1986)	no information available	Deer Trail: –1.1 (gn) 0.6 (sl) 2.0 (cpy) 3.9 (py) (Beatty <i>et al.</i> , 1986)
(2) Mississippi Valley Deposits		
$T_{\text{homog}} 50\text{--}200^\circ\text{C}$, most in range 100–150°C (Roedder, 1984; Anderson and Macqueen, 1982)	linear arrays, too "young" to fit reasonable age of mineralization; or too "old", e.g., Pine Point.	Pine Point: 18.4 (gn) 19.3 (ms) 19.7 (py) 21.6 (sl) Elk Point: evaporites 19–20 (Kyle, 1981)
Pine Point: 51–99°C >15% NaCl equivalent (Kyle, 1981)		
(3) Kootenay Arc and Irish Deposits		
no information available	moderately radiogenic clustered	–4.1 to –26.1 (sl); equal to values in diagenetic pyrite. Temps inferred 224–298°C (Boast <i>et al.</i> , 1981)

(Heyl *et al.*, 1974; Doe and Delevaux, 1972) and in leaching experiments using Precambrian basement rocks and sandstones from the Mississippi Valley region (Doe and Delevaux, 1972).

The occurrence of the Robb Lake and Pine Point deposits along the same Devonian facies front, and the regional hydrologic interpretation of Garven

(1985) in which the fluids that generated Pine Point had their source regions in the Rocky Mountains, combine to strongly suggest co-genesis. Yet the Pine Point lead isotopic signature is a tight cluster that not only is less radiogenic than the Robb Lake deposits, but also lies considerably below the shale curve itself (Figure 4-12; Cumming *et al.*, 1990). This contrast is unexplained. It seemingly calls for the presence of very primitive lead in the source rocks. The source of such lead in a midcontinental setting is problematic. The Pine Point lead remains an anomaly worthy of study.

The above discussion shows that lead-isotopic signatures from carbonate-hosted ores are very useful as indicators of deposit type and of the contrasting processes by which metals are dissolved in ore fluids. Accurate absolute dating of carbonate-hosted deposits via lead isotopes is chimerical except in certain cases, notably high-temperature mantos in areas where local upper-crustal lead growth curves, such as the shale curve, have been defined.

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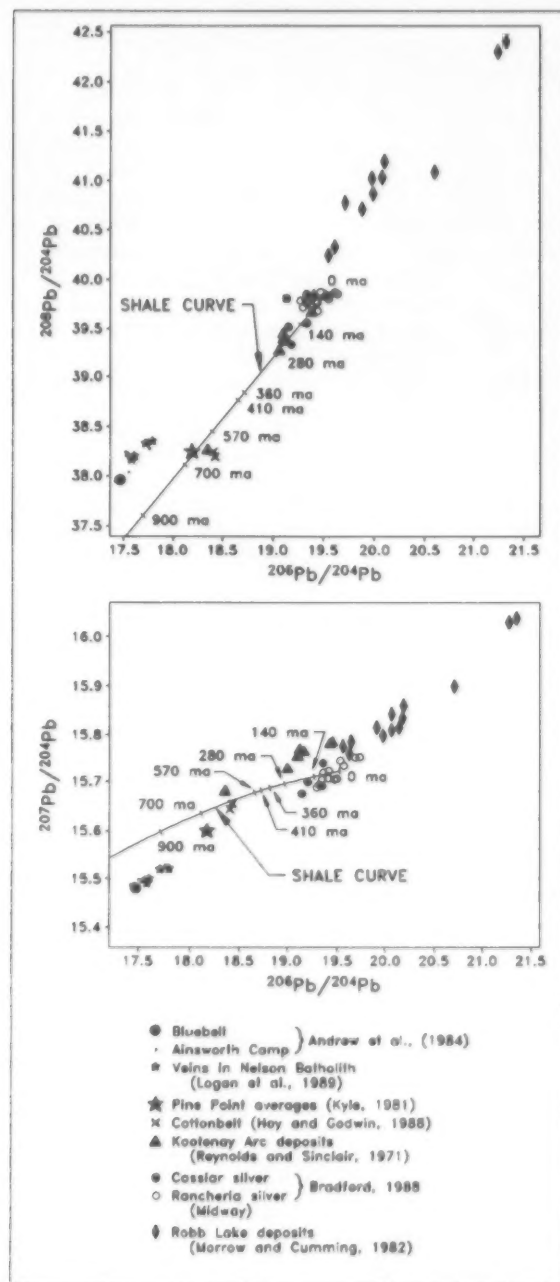


Figure 4-12. Lead isotopic data for carbonate-hosted deposits in the B.C. Cordillera.

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VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS IN BRITISH COLUMBIA

by Trygve Höy

INTRODUCTION

Volcanogenic massive sulphide deposits (VMS deposits) are an important source of copper, zinc, lead and precious metals in Canada and, historically, in British Columbia. In the 1970s, approximately 30 per cent of the copper, 60 to 70 per cent of the zinc, 30 per cent of the lead and 55 to 60 per cent of the silver produced in Canada was mined from VMS deposits (Sangster, 1986; Lydon, 1984). These ratios have remained relatively constant through the 1980s. Although there are only two mines presently working these deposits in British Columbia, a number of others are in advanced stages of exploration and development. Their high grade and commonly high precious metal content make them an attractive exploration target.

Volcanogenic massive sulphide deposits are part of a larger group of concordant massive sulphide deposits that formed by discharge of hydrothermal fluids onto the seafloor. This group includes the sedimentary-exhalite or sedex deposits, typically massive to bedded, concordant lenses of pyrite, sphalerite and galena in basinal shales, greywackes or turbidites. In British Columbia, most sedex deposits are in terrigenous clastic rocks that were deposited at or near the ancestral cratonic margin in Middle Proterozoic or Early Paleozoic time, whereas most VMS deposits formed in Late Paleozoic or

Mesozoic time in volcanic arcs or rifted basins that were accreted to North America. Both classes of deposit share a common genetic link; formed during periods of either local or regional extension.

This paper describes VMS deposits, outlines their tectonic setting and presents genetic models. Comparisons with recent discoveries of active hydrothermal vents and sulphide accumulations in oceanic-ridge environments allows more definitive analysis of the origin and nature of hydrothermal fluids, the mechanisms of discharge and the accumulation and preservation of sulphide masses. Volcanogenic massive sulphide deposits in British Columbia are classified and compared to well-known type examples described elsewhere. Finally, the paper attempts to present guidelines for exploration for VMS deposits, including summarizing the tectono-stratigraphic environments that favour their distribution, and presenting structural, lithological, geochemical and geophysical exploration guidelines.

TECTONIC SETTING

Volcanogenic massive sulphide deposits occur in marine volcanic rocks or associated marine sedimentary rocks, commonly close to plate margins (Lydon, 1984; Sawkins, 1990). These include the divergent plate margins, such as oceanic ridges or back-arc basins, or convergent margins including

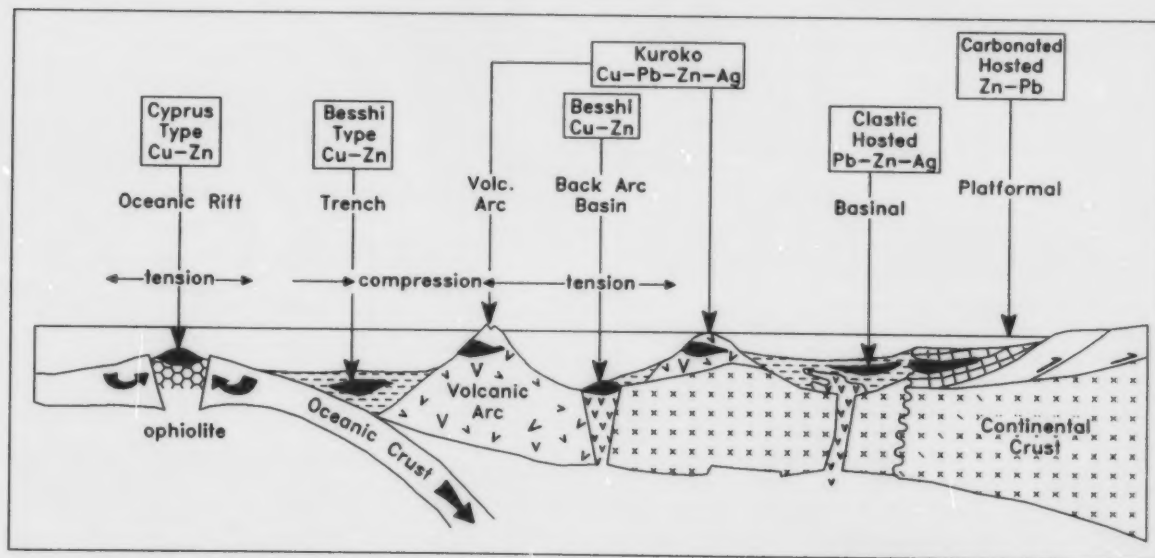


Figure 5-1. Tectonic environments of massive sulphide deposits (modified from Hutchinson, 1980).

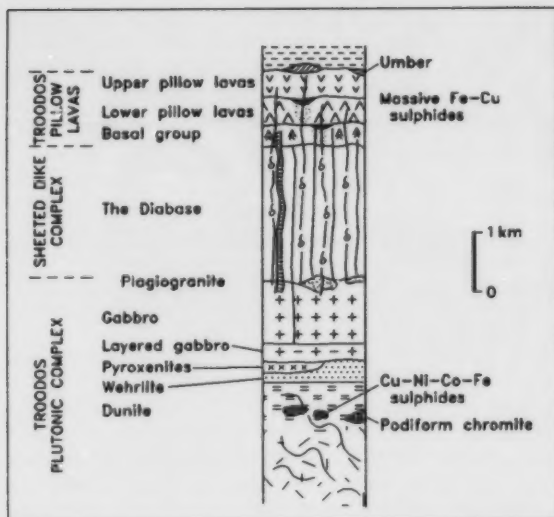


Figure 5-2. Lithostratigraphic section of the Troodos ophiolite complex (after Searle and Panayiotou, 1980; Sawkins, 1990).

island arcs and continental margins (Figure 5-1). Less commonly, marine volcanic rocks and associated VMS deposits occur in intraplate environments, as has been interpreted for the Chu Chua deposit and its hostrocks north of Kamloops (Aggarwal and Nesbitt, 1984).

By far the greatest volume of magma is generated at oceanic spreading ridges (Menard, 1967). Similar magma is also generated in marginal basins behind volcanic arcs and during early stages of continental separation such as occur in the Red Sea and Guaymas Basin in the Gulf of California. It is not surprising, therefore, that VMS deposits formed at these divergent plate margins have similar characteristics; in this report they are collectively referred to as the Cu-Zn type.

A model for the oceanic crust and underlying mantle material is demonstrated in ophiolite complexes (Coleman, 1977). A schematic section through an ophiolite complex, the well-studied though perhaps not well-understood Troodos Complex in Cyprus, is illustrated in Figure 5-2. It comprises a mafic intrusive complex, harzburgite and minor dunite, overlain

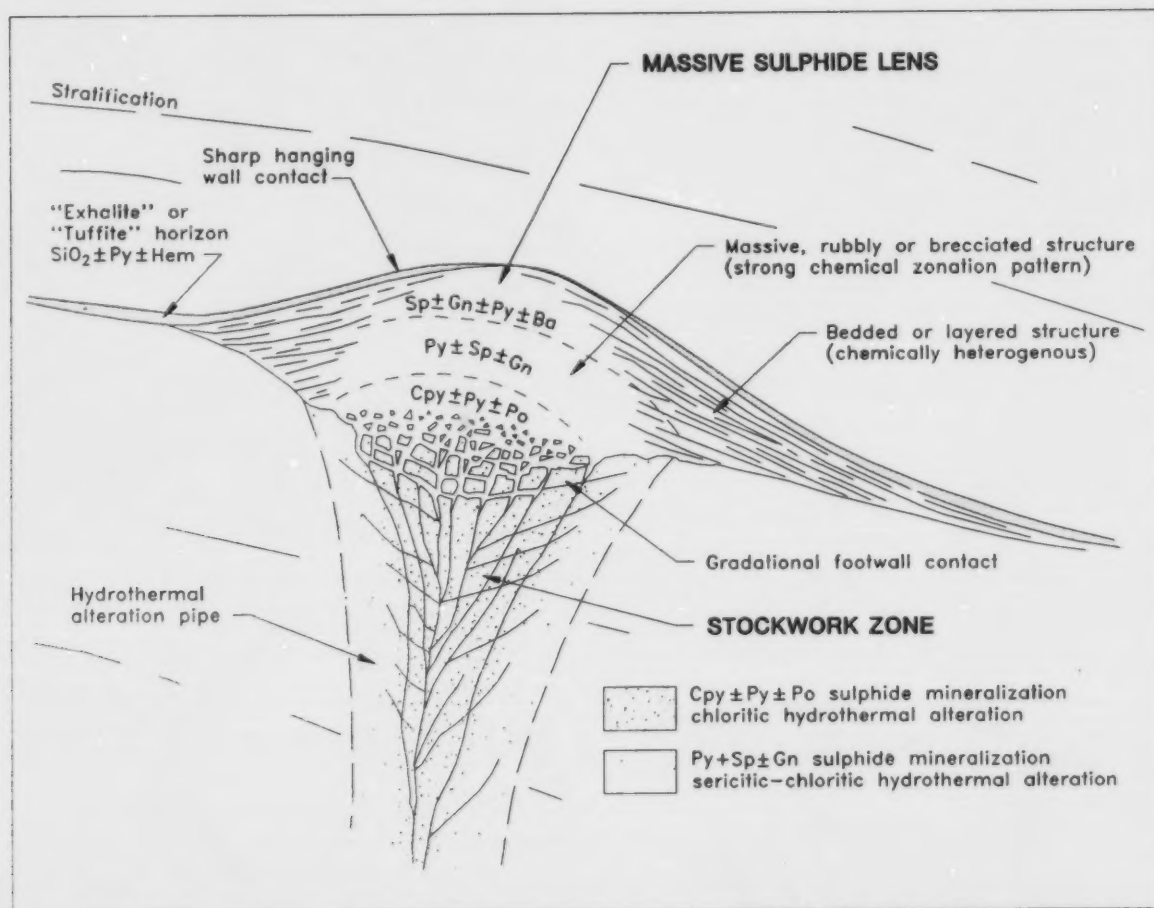


Figure 5-3. Characteristics of an idealized volcanogenic massive sulphide (VMS) deposit (from Lydon, 1984). Ba=barite, Gn=galena, Py=pyrite, Sp=sphalerite, Cpy=chalcocopyrite, Po=pympholite, Hem=hematite, SiO₂=silica.

by pyroxenite, layered and massive gabbro; a sheeted dike complex; and a pillow lava complex with an increasing percentage of dikes and sometimes sills near the base. This succession is overlain by fine pelagic sediments. As most ophiolite complexes have been involved in arc-continent collision, they are typically dismembered, highly deformed and altered. Hence, their recognition in tectonic belts is often difficult.

Many ophiolite complexes are chemically and petrologically similar to mid-ocean ridge basalts (MORB). Others, including the Troodos Complex, have some calcalkaline affinities which suggest that they formed in marginal basins above active subduction zones (Miyashiro, 1973; Thy *et al.*, 1985).

Massive sulphide deposits in ophiolite complexes occur in the mafic pillow lava sequence. They are typically small pyritic, copper-zinc rich and have well-developed stockwork feeder zones. Cyprus deposits are the type examples of this subclass of VMS deposits (see Table 5-1).

Volcanic rocks that formed in the early stages of continental separation, in back-arc basins and in oceanic ridges close to continental margins, have calcalkaline or mid-ocean ridge basalt (MORB) affinities. However, these successions are generally interlayered with terrigenous clastic rocks. In the Guaymas Basin where seafloor hot springs are currently forming massive sulphide deposits, basaltic dikes and sills occur in a thick succession of tur-

bidites. Interlayered basalt and turbidites also typify the succession in the Escanaba Trough near the southern end of Gorda Ridge, and in the vicinity of Middle Valley in the Juan de Fuca Ridge. At this location magma generation at a divergent plate margin is flooded by turbidites from adjacent North America.

VMS deposits formed in these sediment-rift environments have many similarities with the Besshi copper-zinc deposits in Japan. Besshi deposits are tabular, stratiform sulphide accumulations in either the mafic volcanic rocks or the associated clastic rocks.

Polymetallic massive sulphide deposits, or the Kuroko class (Table 5-1), occur most commonly in rocks interpreted to represent arc-related rifts (Sawkins, 1990). Such rifts develop within, or perhaps behind, island arcs in oceanic settings or adjacent to continental margins. Arc volcanism is typically bimodal, calcalkaline, and includes high-alumina basalt, andesite, dacite and rhyolite. Although basalt and andesite are usually the most voluminous rocks in these calcalkaline volcanic suites, the massive sulphide lenses are generally within or adjacent to fragmental dacitic or rhyolitic rocks.

The tectonic setting and types of various massive sulphide deposits, including VMS and sedex deposits, are schematically summarized in Figure 5-1. Carbonate-hosted lead-zinc deposits occur in miogeoclinal limestone or dolomite above continental crust and sediment-hosted lead-zinc deposits in marine or perhaps lacustrine clastic rocks also generally above continental crust. Volcanogenic deposits are within or closely associated with marine volcanic rocks in a diverse suite of tectonic settings; in tholeiites in mid-ocean rift environments, in intraplate oceanic islands, in mixed basalts and terrigenous clastic rocks in back-arc basins or continental margin settings, or in rifts in volcanic arcs above subducting plates.

TABLE 5-1

Classification of Volcanogenic Massive Sulphide Deposits in British Columbia

	Cyprus	Cu-Zn Besshi	Zn-Pb-Cu Kuroko
Tenor	Cu-(Zn)	Cu-Zn-(Pb)	Zn-Pb-Cu-Au-Ag
Volcanic association	tholeiitic	calcalkaline	bimodal, calcalkaline
Host	basalt	basalt, terrigenous rocks	felsic pyroclastics
Tectonic setting	oceanic ridge	continental margin, back-arc	island arc
Alteration; Association	stringer zone chloritic Fe-Mn chert	chloritic silicification Fe-Mn chert	stringer zone silicification sericitic sulphates
Examples	Anyox Chu Chua	Goldstream Granduc Windy Craggy	Rea Homestake Lynx Kutcho Creek Tulsequah Chief

DEPOSIT MORPHOLOGY

An idealized VMS deposit is illustrated in Figure 5-3. It consists of a concordant lens of massive sulphides that stratigraphically overlies a crosscutting, discordant zone of intense alteration and stockwork veining. The sulphide lens may be overlain or flanked by thin, siliceous iron or manganese-rich siliceous strata (Hutchinson, 1973) or by sulphate rock. Typically, the upper contact of the massive sulphide (or sulphide-sulphate) lens is in sharp contact with overlying sedimentary or volcanic rocks, whereas the lower contact may be sharp or gradational into the stockwork zone. The sulphide lens commonly extends beyond the limits of the stockwork zone, as illustrated in Figure 5-3, or may be spatially removed either due to initial deposition or to later structural deformation (Sangster, 1972).

Pyrite is the dominant sulphide in most VMS deposits. Zoning of other sulphide minerals or metals is prominent within some massive sulphide lenses. The tops are often zinc or zinc-lead rich whereas the bases are commonly copper-rich and pyrrhotitic. In Kuroko deposits, this copper-rich or chalcopyrite dominated ore is referred to as "yellow ore" whereas the galena-sphalerite rich portion is referred to as "black ore" (Ohmoto and Skinner, 1983). This zoning is so characteristic in many massive sulphide deposits that it can be used to determine stratigraphic tops.

Lateral metal and mineral zoning are also common, with central portions giving way laterally to thinner and commonly laminated pyrite, galena and sphalerite-rich zones, and distal barite, anhydrite, and/or chert. Precious metal contents of VMS deposits are variable. Enrichment may occur in the copper-rich stockwork zones and in the upper and distal portions of the massive sulphide lenses (Sawkins, 1990).

Sulphides are most commonly compact, massive or crudely layered. Fragmental textures, with clasts ranging in scale from microscopic to deposit size, are common. Sedimentary textures include graded and laminated beds, particularly in distal ores. Metamorphism and deformation has commonly obliterated many primary sulphide textures producing gneissic orebodies.

ALTERATION ZONES

Alteration zones associated with VMS deposits are often considerably larger than the deposits themselves and hence their recognition can be a valuable exploration tool. A number of zones of alteration are commonly recognized; the footwall alteration pipe, alteration associated with the ore horizon, a large semiconformable zone beneath the ore horizon, and hangingwall alteration.

Pipe-like footwall alteration zones are interpreted as the channelways for hydrothermal fluids that precipitate sulphides at or near the sediment-seawater interface. The various footwall alteration assemblages reported for VMS deposits are schematically summarized in Figure 5-4. At the Millenbach deposit in the Abitibi Belt in the Canadian Shield, the footwall alteration pipe comprises an inner chloritic zone surrounded by a peripheral sericitic zone (Riverin and Hodgson, 1980). The chloritic zone is characterized by addition of iron and magnesium and by depletion of calcium, sodium and silicon. Potassium may be depleted in the chloritic zone but is enriched in the sericitic zone. With intense magnesium and iron metasomatism, talc and actinolite may develop, as is documented at the Chu Chua deposit (Aggarwal and Nesbitt, 1984).

Many other deposits have pronounced footwall chlorite-quartz alteration zones. Quartz and chlorite are also common as gangue within the sulphide

lenses and as matrix to sulphide clasts and grains. This chlorite or chlorite-quartz alteration is particularly common in deposits hosted by mafic volcanic rocks.

Quartz-sericite altered footwall rocks are common in many of the VMS deposits in British Columbia. Commonly, the silica-sericite alteration zones are surrounded by more extensive magnesium-rich chlorite zones. In some cases (Rea Gold, Windy Craggy), the quartz-sericite alteration is so intense that it masks the original composition or texture of the host volcanic rocks. Intense silicification may occur in the upper part of the alteration zone adjacent to the overlying VMS deposits while sericite-rich alteration is generally more widespread. Similar footwall sericite-silica alteration assemblages have been described for Kuroko deposits. When completely developed, a central core of sericite-quartz-pyrite is surrounded successively by chlorite-quartz-sericite, clay-sericite-chlorite-quartz, albite-sericite-chlorite-quartz and finally kaolinite-quartz-sericite (Iijima, 1974).

Carbonate alteration, commonly in the form of siderite or ankerite, occurs in the footwall of some Kuroko deposits, usually associated with either chlorite, sericite or silica alteration.

Alteration within and along the ore horizon is also common. Within a VMS deposit it occurs as crosscutting veinlets of quartz, sericite or chlorite and as pervasive quartz, silicates and carbonate in the groundmass of sulphide grains and clasts. Regional alteration along the ore horizon is less well documented although exhalites may extend well beyond the limits of the ore lens. The ochre horizon

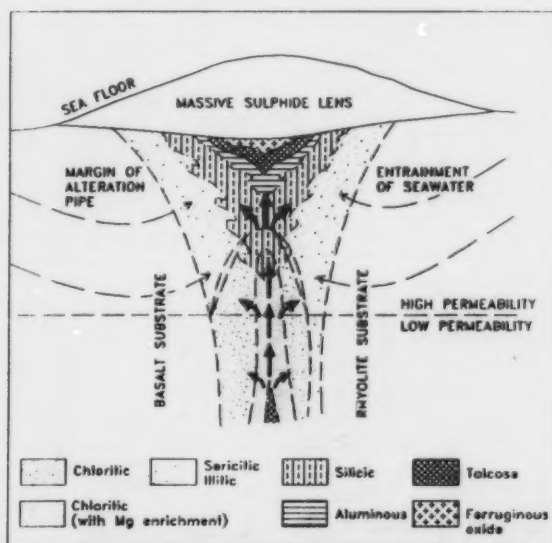


Figure 5-4. Composite representation of various alteration assemblages that have been reported for alteration pipes of VMS deposits (from Lydon, 1988).

in Cyprus deposits (Constantinou, 1980) and regional dolomite at Kutcho Creek (Bridge *et al.*, 1986; Panteleyev and Pearson, 1977) are examples.

A major alteration type associated with some VMS deposits is the much larger, semiconformable zones that may exist beneath the ore horizons (Morton and Franklin, 1987). They may grade laterally or vertically into the crosscutting alteration pipes or are overprinted by these pipes. They can have a strike length of several kilometres and thicknesses of hundreds to thousands of metres.

Morton and Franklin (1987) recognize a two-fold classification of Archean VMS deposits, each with distinct alteration zones (Figure 5-5). Noranda-type deposits occur in mafic and felsic flows and hyaloclastites and have an irregularly distributed, patchy, semiconformable alteration zone of silicification and spilitization. Spilitized rocks are composed of epidote and quartz with or without albite, tremolite-actinolite and magnesium-chlorite. Mattabi-type deposits have a higher proportion of felsic volcanic rocks in their footwall, a large, well-defined semiconformable alteration zone that may extend up to the ore horizon and may merge with the pipe alteration. Alteration minerals in Mattabi-type deposits occur as two distinct assemblages: sericite

and quartz, commonly with dolomite; and iron chlorite, iron carbonate and, at higher metamorphic grades, chloritoid and andalusite-kyanite.

Lack of explosively-formed fragmental rocks, sub-aerial volcanic rocks and evidence of vigorous vesiculation suggests that hostrocks for Noranda-type deposits formed at water depths of more than 500 metres (Gibson *et al.*, 1983; Morton and Franklin, 1987). Mattabi-type deposits, however, are believed to occur in volcanic rocks at shallower water depths. Sericite in the semiconformable alteration zones beneath Mattabi deposits may be due to shallow circulating seawater which interacted with rocks at relatively low water:rock ratios and low temperatures (<250°C), leaching sodium, iron and magnesium and depositing potassium.

Alteration of hangingwall rocks may indicate that hydrothermal fluids continued to circulate after deposition of the sulphides. This alteration, when present, is far less extensive or intense than footwall alteration. It is noted in a few VMS deposits, including the lower Amulet A and Corbett deposits (Knuckey and Watkins, 1982) in the Noranda area (Franklin *et al.*, 1981; Gibson *et al.*, 1983), and in many of the Kuroko deposits (Sawkins, 1990).

GENESIS

It is now generally accepted that volcanogenic massive sulphide deposits were formed on or close to the seafloor (Oftedahl, 1958). The massive sulphide lens represents the accumulation of sulphides precipitated from hydrothermal solutions at a discharge vent, and the stockwork zone the channelway for the ascending hydrothermal fluids. The recent discovery of hydrothermal vents and massive sulphide accumulations in modern submarine spreading centres has sparked considerable research and added substantially to our understanding of the setting and the formation of ancient deposits.

A number of requirements are essential for the formation and preservation of massive sulphides on the seafloor (Scott, 1985). These include: a fluid capable of carrying metals and reduced sulphur in solution; a heat source; a fracture system; a mechanism for precipitating sulphides; and preservation by burial. Studies of modern venting hydrothermal fluids, combined with numerous studies of ancient deposits, indicate that the fluids are mainly of seawater origin. As seawater penetrates heated crustal rocks to depths of 3 kilometres, it reacts with basalt producing a hot, strongly reduced, weakly acidic fluid with salinities up to twice that of seawater (Hutchinson *et al.*, 1980; Lydon, 1988). Initially, at shallow depths, anhydrite precipitates due to the reverse solubility of anhydrite with temperature, and magnesium is removed from the fluid in exchange for calcium. Talc and, at increasing depth, epidote form increasing the acidity of the solution. Metals, including copper, zinc, lead, manganese and pre-

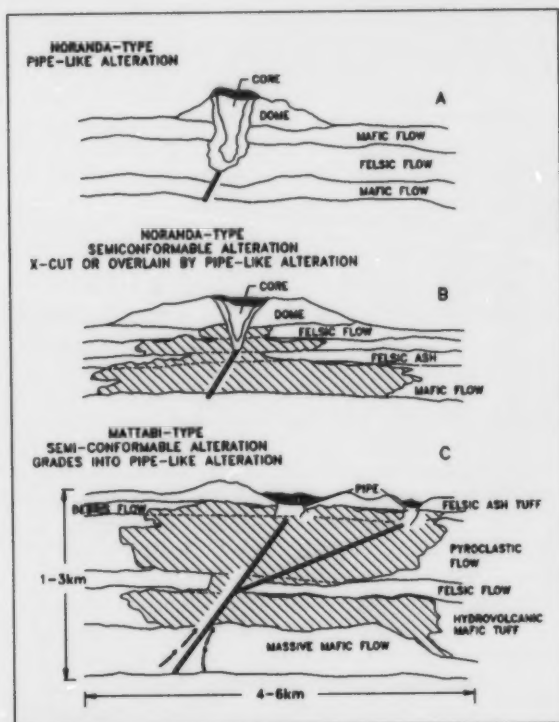


Figure 5-5. Generalized diagram of pipe and semiconformable alteration zones associated with Noranda and Mattabi-type massive sulphide deposits (from Morton and Franklin, 1987).

cious metals, are leached from the rock column; in general, the metal ratios in VMS deposits are similar to the ratios of the source rocks. The resultant hydrothermal solutions are transported upwards, commonly along crustal breaks or fault structures and eventually disperse in the seawater or precipitate metals forming mineral deposits or occurrences.

Deposition of transported metals begins as the deeply-circulated hydrothermal fluids approach the seafloor and react with shallow-circulated, cooler and relatively oxidized fluids. Magnesium, silica and potassium are precipitated resulting in footwall chloritic and sericitic alteration and silicification. Rapid pressure decrease may cause boiling resulting in phreatic explosions, fracturing and brecciation of footwall rocks. These processes can result in the characteristic stockwork zone beneath VMS deposits characterized by veining, brecciation and complex alteration patterns.

Direct deposition of sulphides and sulphates onto the seafloor and subsequent replacement reactions produce the massive sulphide lenses. Sato (1972) describes three basic types of venting hydrothermal fluids, resulting in sulphide accumulations as fallout from hydrothermal plumes (Figure 5-6). Type I solutions, with high salinities, collect as brine pools in the deepest part of axial valleys. Red Sea brines, with temperatures of about 200°C and salinities up to seven times that of seawater, are similar to these Type I solutions (Schoell, 1976; Zierenberg *et al.*, 1984). Type II solutions are initially lighter than seawater, but with mixing with seawater can form heavy brines with resultant sulphide accumulations. Type III solutions, however, form bouyant plumes with resultant dispersal of metals. Hydrothermal plumes observed in the Eastern Pacific Rise, the black smokers, are similar to Sato's Type III solutions.

Discovery of mound-chimney deposits on the ocean floor (Rona, 1978) has confirmed the basic model for formation of volcanogenic massive sulphide deposits, but has also allowed some revision in the actual processes of sulphide accumulation. The accumulation of sulphides from black smokers is inefficient as metals carried in the fluids are largely dispersed in the seawater or produce only distal metal-enriched haloes. Cann *et al.* (1985) developed a computer model that involved periodic catastrophic changes in vent flow, a model that has been corroborated by observations of megaplumes in the Juan de Fuca ridge (Baker *et al.*, 1987). Catastrophic surges occur when critical emission temperatures of approximately 400°C are attained and pressure increases result in brecciation, enhanced permeability and large amounts of sulphide emission. This model has been applied to the Sulitjelma Cu-Zn orebodies in northern Norway (Cook *et al.*, 1990).

Lydon (1988) proposed a model of sulphide accumulation by replacement of collapsed sulphide-sulphate chimney mounds. Sulphide deposits near

vents are dependent on initial precipitation of anhydrite, from seawater, due to its decreased solubility with increasing temperature. Sulphides form by replacement of anhydrite and by infilling of pore spaces. As a chimney grows, the walls of the lower part thicken by precipitation of sulphides in the inner portions and anhydrite in the outer portions.

Fluids in the chimney wall have a steep physiochemical gradient, from high temperature (300°C),

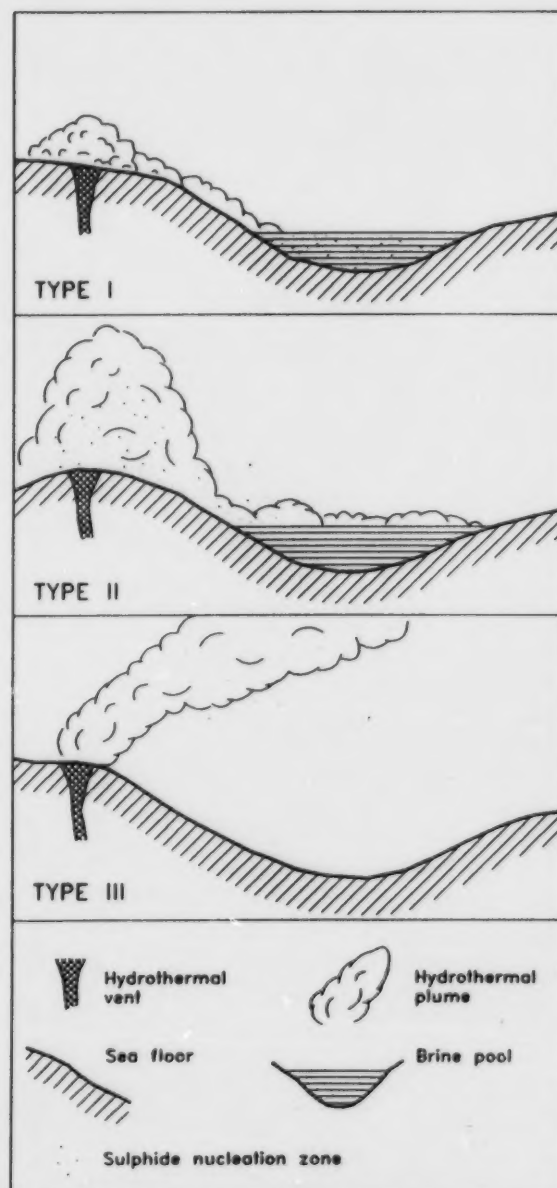


Figure 5-6. Models showing probable behaviours of ascending hydrothermal fluids onto seafloor, according to various temperature-salinity factors (from Lydon, 1988; after Sato, 1972).

acid, reduced conditions on the inside, to low temperature (2°C), alkaline, oxidized conditions approaching that of seawater, on the outside. This results in a characteristic zonation in a mature chimney wall (Figure 5-7), from chalcopyrite on the inside, to pyrite-sphalerite and wurtzite in an anhydrite matrix, to an exterior zone of anhydrite with minor sulphides, barite and silica. With increased growth, a chimney becomes unstable and collapses forming a mound of chimney talus. This process eventually results in a sulphide mound and continued sulphide replacement reactions at the base of the mound can lead to a vertically and laterally zoned deposit, with higher temperature minerals replacing overlying lower temperature minerals (Figure 5-8).

Other factors that are necessary, or which enhance massive sulphide accumulation and preservation, are a heat source of sufficient size to drive large-scale circulation of seawater and hydrothermal fluids

through several kilometres of ocean floor rocks. A heat source is most commonly a large, high-level synvolcanic intrusion; less commonly, suites of mafic sills or dikes, as in the Purcell basin that hosts the Sullivan deposit, can provide a heat source (Höy, 1989). A magma chamber may also provide a source of some of the metals, as has been proposed by Sawkins (1986) and others.

A fracture system enhances fluid circulation and focuses the discharge. Syndepositional faults or fracture systems are recognized in the vicinity of many ancient VMS deposits (Figure 5-9), and deposits in camps can often be aligned along structural lineaments (Scott, 1980). These structural controls are particularly well recognized in localizing massive sulphide accumulations and hydrothermal vents in the northeast Pacific spreading centres (Kappel and Franklin, 1989).

Preservation of a sulphide mound in oxidized waters on the sea floor requires an insoluble cap or burial by new volcanic and sedimentary rock. As Cathles *et al.* (1983) and Scott (1985) have pointed out, a submarine rift is an environment that satisfies many of the criteria required for VMS deposition: high heat-flow, underlying magma chamber, intense fracturing and commonly, rapid burial.

DISTRIBUTION

Volcanogenic massive sulphide deposits range in age from Archean to Recent (Hutchinson, 1980). They are distributed throughout the world and include the actively forming deposits in mid-ocean environments. They are particularly well known in Canada, Japan, U.S.A., Australia and parts of Europe.

Archean volcanic rocks in the Canadian Shield contain numerous large and well-studied VMS deposits. These include the deposits of the Noranda Camp: the Home mine, Quemont, Amulet, Millenbach and Corbet; Kidd Creek near Timmins, Ontario; and the Sturgeon Lake camp, northwest of Thunder Bay. Archean rocks elsewhere, including the shield areas of South Africa and Australia, do not contain similar clusterings of important VMS deposits.

Deposits of Early Proterozoic age (1900–1700 Ma) include those at Flin Flon and Snow Lake, Manitoba, in the Whitewater Group of the Sudbury Basin and at Jerome and Prescott, Arizona. Mid-Proterozoic VMS deposits are uncommon (Hutchinson, 1980; Sangster, 1980); however, numerous large and important sedex massive sulphide lead-zinc deposits, including the Sullivan deposit at Kimberley, British Columbia, occur in clastic rocks of this age. Late Proterozoic VMS deposits include those at Ducktown, Tennessee.

Most Paleozoic VMS deposits appear to cluster in two age spans; Middle to Late Ordovician and Late Devonian. The Buchans camp, Newfoundland, has

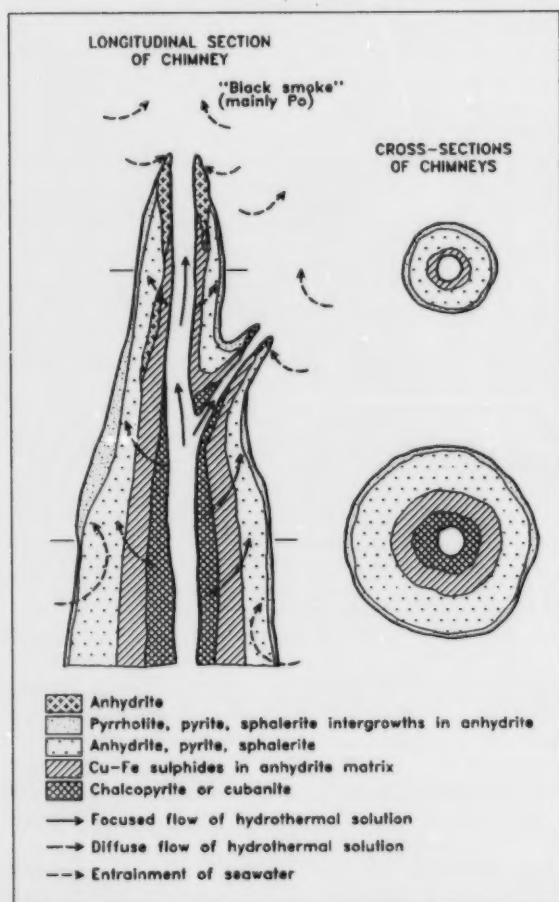


Figure 5-7. Mineral zoning of a modern, ideal "black smoker" sulphide chimney (from Haymon *et al.*, 1984; Lydon, 1988).

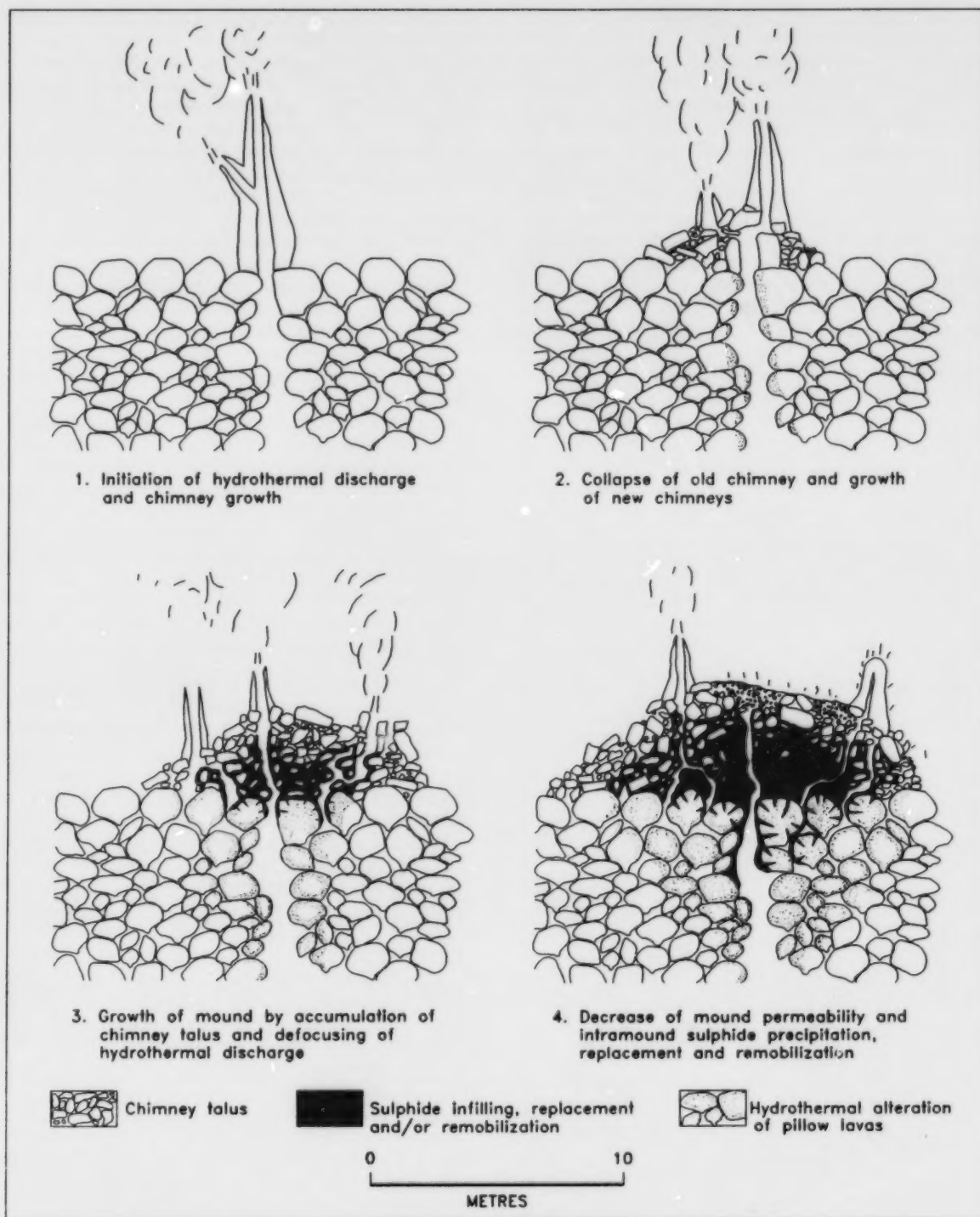


Figure 5-8. Schematic representation of the growth of a modern mound-chimney sulphide deposit (from Lydon, 1988).

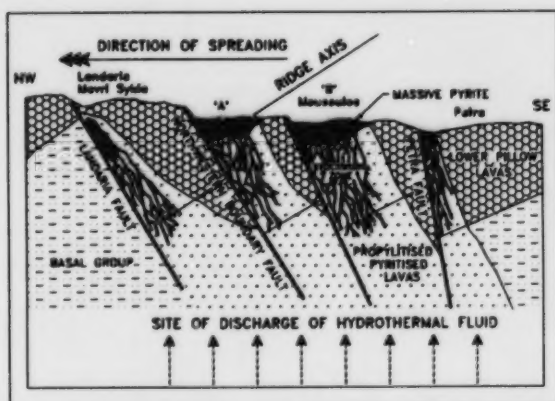


Figure 5-9. The environment of formation of the Cyprus Kalarasos deposits, showing clustering of deposits and structural controls (after Adamides, 1980).

produced approximately 18 million tonnes of ore from a number of orebodies in the Late Ordovician Buchans Group (Thurlow and Swanson, 1981). Other "Early" Paleozoic VMS deposits include those in the Bathurst camp, New Brunswick; West Shasta, California; the Tasman belt, Australia; Ordovician deposits in the Norwegian Caledonides and the oldest VMS deposits of the Canadian Cordillera, the copper-zinc deposits of the Goldstream camp, north of Revelstoke.

There are many VMS (and sedex) deposits of middle Paleozoic age in the Canadian Cordillera (Table 5-2). These include numerous lead-zinc-copper deposits in the Late Devonian Eagle Bay assemblage northeast of Kamloops and in the Late Devonian Sicker Formation on Vancouver Island. The Rio Tinto deposit in the Iberian pyrite belt in Spain is one of the world's largest massive sulphide deposits (Williams *et al.*, 1975). The age of the host succession is bracketed by an underlying Late Devonian flysch sequence and overlying Carboniferous succession. The Besshi deposits in Japan are "late" Paleozoic.

Volcanogenic massive sulphide deposits occur throughout the Mesozoic, including numerous Late Triassic deposits in British Columbia - Kutcho Creek, Windy Craggy, Granduc and a number of deposits in the Anyox area. Although arc volcanics occur in the Jurassic in British Columbia, there are few well-documented examples of VMS deposits of this age. The Seneca deposit in the Harrison Lake Formation and a number of unusual high-silver deposits such as Eskay Creek and those of the Dolly Varden camp are in Middle or Late Jurassic rocks. The Turner Albright deposit in Oregon, is a copper-zinc deposit in Late Jurassic ophiolites (Saleeby *et al.*, 1982). The well-known Cyprus deposits are Late Cretaceous in age and the Britannia deposits in

southwestern British Columbia are in the Cretaceous Gambier Group.

Tertiary deposits are exemplified by the Kuroko deposits in Japan; these are in Miocene fragmental rocks. The Sunro deposit at Jordan River, Vancouver Island, is a possible VMS deposit in the Metchosin Formation, a Middle Eocene ophiolite complex (Massey, 1986).

CLASSIFICATION

Classification of volcanogenic massive sulphide deposits is often difficult as most deposits share characteristics of a number of different classes; others do not fit into any distinct class. However, classification schemes do allow comparisons and contrasts between various deposits. These schemes generally place emphasis on either the metal content of the deposit or their tectonic setting.

Classifications based on hostrocks or tectonic setting are useful as they provide information critical to exploration. However, the settings are not always well known and therefore assignment by ore composition becomes more practical. Solomon (1976), Franklin *et al.* (1981) and Franklin (1986) proposed a classification into copper-zinc and zinc-lead-copper types. Hutchinson (1973) proposed a three-fold subdivision: Archean volcanic-hosted zinc-copper deposits, volcanic and mixed sediment-volcanic-hosted lead-zinc-copper-silver deposits of mainly Proterozoic and Phanerozoic age, and mafic volcanic-hosted cupriferous pyrite deposits of principally Phanerozoic age. A classification suggested by Sawkins (1976), based on setting and associated volcanics, has become fairly widely accepted: Cyprus-type deposits are in mafic volcanic rocks, usually ophiolites, in spreading ocean or back-arc ridges, Besshi-type deposits are in calcalkaline volcanics and sediments in epicratonic rift environments, and Kuroko-type deposits occur in more felsic volcanic rocks in volcanic arcs.

The subdivision adopted in this paper (Table 5-1) combines the elements of ore composition, tectonic setting and hostrocks, an approach similar to that proposed by Hutchinson (1980). Volcanogenic massive sulphide deposits are subdivided into two broad types: copper-zinc and zinc-lead-copper. The first class includes both Cyprus and Besshi-type deposits, whereas the second type is similar to Kuroko deposits.

It is not always possible to clearly assign all VMS deposits to one of these classes, in part due to lack of information on some deposits and in part because classes may be ideal end-members in a continuum.

CU-ZN DEPOSITS — CYPRUS-TYPE

Cyprus-type deposits, as described in the section on tectonic setting, ideally occur in tholeiitic basalts formed in mid oceanic ridge or marginal basin

environments. The sulphide deposits in the Troodos Complex in Cyprus all occur within the pillow lava sequence. Although most of the Cyprus deposits are less than 100 000 tonnes, at least six exceed one million tonnes in size. In a number of instances, groups of small Cyprus deposits cluster close to one another (Figure 5-9).

Cyprus deposits generally consist of a lens of massive sulphides underlain by a well-developed pipe-shaped stockwork zone (Figure 5-10). The massive sulphide lens consists of fine-grained pyrite and chalcopyrite, with accessory marcasite, sphalerite and galena. The top of the lens may be altered to a goethitic material, interpreted to be caused by submarine oxidation and indicative of formation on the seafloor (Constantinou and Govett, 1972). The massive sulphide lens is usually overlain by unmineralized deep-water marine sediments or by pillow lavas.

Stockwork zones beneath Cyprus deposits consist of strongly altered and mineralized basalt. Mineralization occurs disseminated or as quartz-chlorite veins and veinlets with chalcopyrite and pyrite. In many deposits, the stockwork mineralization is ore; other stockworks are too small or are dominantly pyritic.

Cu-Zn DEPOSITS — BESSHI-TYPE

Deposits referred to as Besshi-type occur in either mafic volcanic rocks or terrigenous clastic rocks interlayered with flows or sills. These rocks were deposited in a rift environment – in oceanic ridge environments close to continental margins, in back-arc basins, and possibly in intracratonic basins (see Figure 5-1).

The Besshi mine is the largest of more than a hundred copper-zinc deposits in the San Bagawa metamorphic belt of southwestern Japan. The deposits occur in the Yoshinogawa Group, a thick sequence of Late Paleozoic terrigenous clastic and carbonate rocks, and interlayered mafic volcanic rocks. Most deposits are at or near a specific stratigraphic horizon in the central part of the group – the contact between mafic volcanic-rich rocks of the Middle Member of the Minawa Formation and argillites in the Upper Member (Franklin *et al.*, 1981).

The Besshi mine produced 33 million tonnes containing 2.6 per cent copper until its closure in 1973. The deposit was a tabular sheet of massive sulphides with a strike length of 1700 metres, a down plunge extent of 3500 metres and an average thickness of 3 metres (Figure 5-11). It is in intensely deformed rocks; the remarkable lateral extent of this thin sulphide layer is probably due, in part, to structural attenuation.

Immediate hostrocks are interbedded basaltic, argillaceous and arenaceous schists, overlain by dominantly argillaceous rocks. The footwall and ore

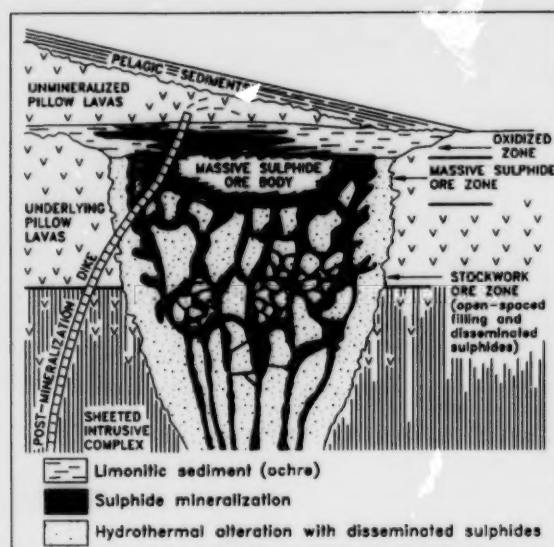


Figure 5-10. Diagram showing the main features of a Cyprus-type volcanogenic massive sulphide deposit (from Spooner, 1980, modified from Hutchinson and Searle, 1971).

horizon are quartz-rich and contain piemontite, spessartine and carbonate. Fox (1984) suggests that these may represent a manganiferous exhalite facies.

The massive sulphide layer comprises dominantly massive and banded pyrite and chalcopyrite, with minor sphalerite, magnetite and hematite. The banded ore occurs in the middle of the sulphide layer and consists of pyrite and chalcopyrite interlayered with magnetite-chlorite-quartz schist. Pyrrhotite is present in some of the deeper levels of the Besshi deposit and cobaltite has been identified locally.

A footwall alteration zone, similar to those recognized in other copper-zinc deposits and lead-zinc-copper deposits has not been recognized. This may be due, however, to obliteration or masking by intense deformation and regional metamorphism. Other Besshi-type deposits, including Goldstream north of Revelstoke (Höy *et al.*, 1984), have variably developed silica-chlorite alteration zones. Although metal zoning is not a common feature of many Besshi deposits, Goldstream has a well-defined lateral zonation that may record an initial "stratigraphic" zonation.

ZN-Pb-Cu ($\pm$ Au, Ag) DEPOSITS — KUROKO-TYPE

Deposits of the zinc-lead-copper class or "Kuroko-type" typically occur associated with explosive felsic volcanism in arc-related rifts. Thus, this tectonic setting, in areas dominated by convergent or "destructive" plate margins, contrasts

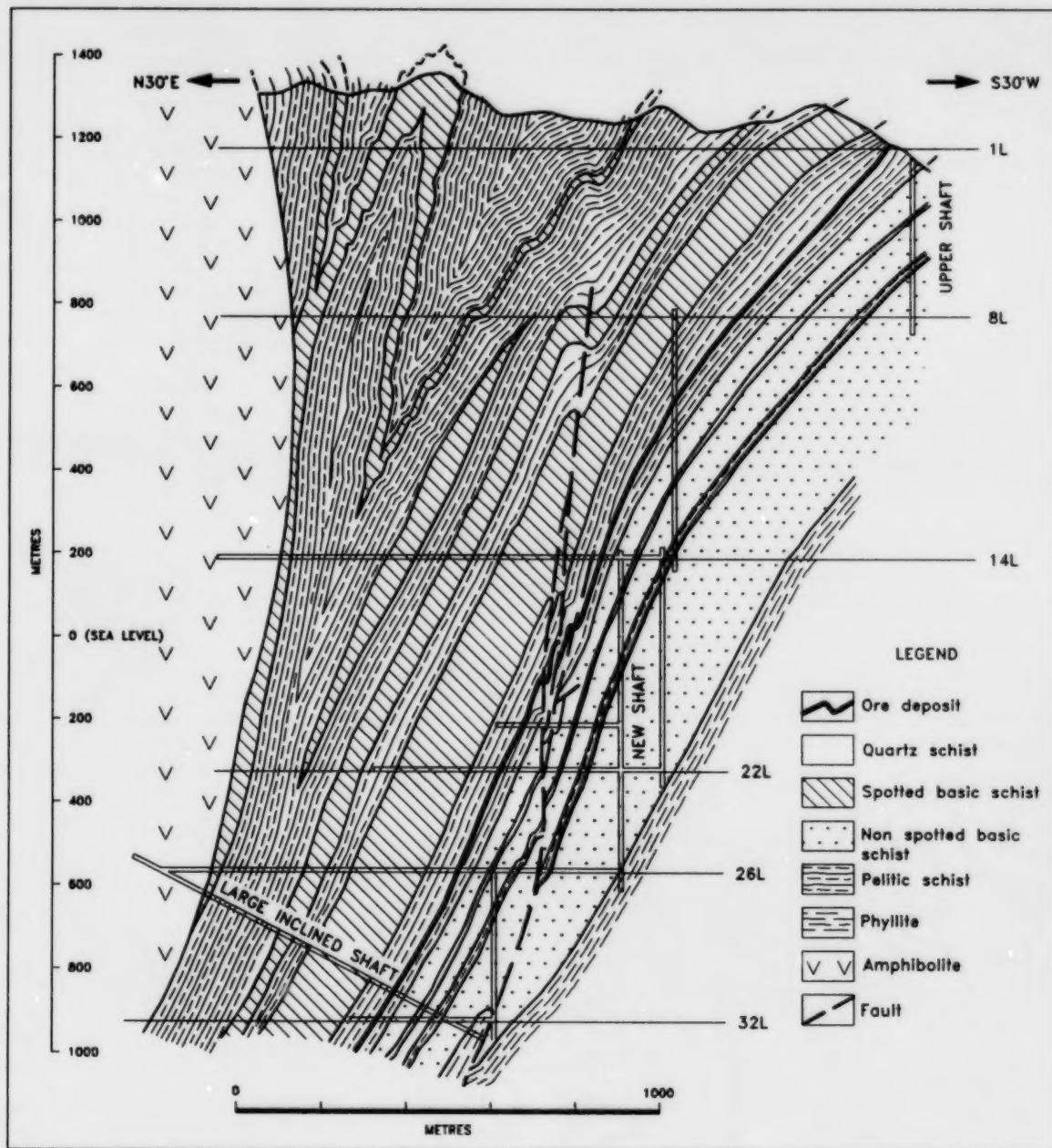


Figure 5-11. Cross-section through the Besshi deposit, Japan (from Franklin et al., 1981).

with the "constructive" plate margin setting of copper-zinc Besshi and Cyprus deposits. As Kuroko-type deposits commonly contain lead and precious metals in addition to copper and zinc, they are also referred to as polymetallic VMS deposits.

The type Kuroko deposits (Ohmoto and Skinner, 1983) occur within the Miocene Green Tuff belt of Honshu and Hokkaido in Japan. Other similar deposits occur in the Hokuriku district of Japan. All deposits are temporally and usually spatially related to explosive submarine felsic volcanism, commonly occurring near the end of a major pulse of volcanic activity. Urabe (1987) notes that deposits coincide with a peak in bimodal volcanic activity and increased and rapid subsidence. This subsidence may be due to collapse-caldera structures (Sillitoe, 1980; Ohmoto and Takahashi, 1983). It may occur during periods of extension in island arcs, possibly during opening of associated back-arc basins or during an abortive interarc rifting episode (Cathles *et al.*, 1983).

An idealized Kuroko deposit is illustrated in Figure 5-12. It comprises three main zones: a low grade stockwork zone with quartz veins, pyrite and chalcopyrite; yellow ore (Okobre) consisting mainly of pyrite and chalcopyrite; and overlying black ore (Kuroko) - massive galena, sphalerite and barite with variable amounts of chalcopyrite and pyrite. The massive sulphide lens may be overlain locally by barite containing minor pyrite, and occasionally by ferruginous chert.

Alteration zones in Kuroko deposits are well displayed. The stockwork zone and immediate deposit are characterized by magnesium chlorite-sericite alteration and, locally, silicification. Less intense sericite, sericite-montmorillonite and chlorite alteration surrounds the stockwork zone and may extend several hundred metres into the hangingwall. Locally, albite and potassium-feldspar occurs within this alteration. Clay alteration, dominantly montmorillonite, extends well beyond the limits of the immediate deposit alteration and grades laterally into regional zeolite facies metamorphism characteristic of the Green Tuff beds. The immediate deposit alteration patterns reflect strong magnesium metasomatism and, in the deposit footwall, silica and potassic metasomatism. The latter metasomatism is locally intense, producing quartz-sericite "white rhyolite" domes from original dacite. Sodium and calcium are depleted, due to the breakdown of feldspars.

VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS IN BRITISH COLUMBIA

Numerous significant VMS deposits or occurrences are known in British Columbia (Table 5-2). Most of these cluster in a number of camps, including the copper-zinc deposits of the Goldstream area, polymetallic lead-zinc-copper deposits in the Barri-

ere area, a number of deposits in the Late Devonian Sicker Group on Vancouver Island, and the past producers at Anyox south of Stewart (Figure 5-13). Windy Craggy, with reserves of 210 million tonnes containing 1.59 per cent copper and 0.09 per cent cobalt is the largest known VMS deposit in the province. The Tulsequah area is receiving renewed exploration interest due to a substantial increase in reserves at the Tulsequah Chief deposit (Table 5-3). Although many of these deposits are past producers (Table 5-4) and others are in advanced stages of exploration, the only current production is from the deposits at Buttle Lake on Vancouver Island and, in 1991, Goldstream in southeastern British Columbia. In 1989, the production at Buttle Lake totalled 22 675 tonnes of copper, 127 tonnes of lead, 32 778.5 tonnes of zinc, 21 490 kilograms of silver and 1212.9 kilograms of gold.

This section attempts to classify VMS deposits in British Columbia, describes a number of type examples, outlines structural and lithological controls, and summarizes main exploration criteria.

CLASSIFICATION

Most VMS deposits in British Columbia fall into the two-fold classification based on metal content: copper-zinc or zinc-lead-copper. Copper-zinc deposits have little, if any, lead associated with them and most commonly occur in mafic volcanic rocks or metasediments associated with mafic volcanic rocks. Further subdivision of the copper-zinc class into Cyprus or Besshi-type is dependent on host lithology. Cyprus-type deposits occur in successions that can be compared to a classical ophiolite sequence and hence are dominated by mafic pillow basalts and possibly associated mafic to ultramafic intrusive rocks. These include the Chu Chua deposit and the Anyox deposits (Table 5-2). Besshi-type deposits occur in successions that include a considerable proportion of terrigenous clastic rocks (continentally derived sedimentary rocks) or that are underlain by these rocks. Goldstream in southeastern British Columbia, Windy Craggy, Greens Creek in Alaska and Granduc are interpreted to be Besshi-type deposits.

Deposits of the zinc-lead-copper class, the Kuroko-type deposits, are more common. These deposits are in bimodal, calcalkaline volcanic rocks that have felsic pyroclastic component. Commonly they are closely tied, both spatially and temporally, with either dacite or rhyolite within an otherwise mafic pile. They are interpreted to have formed in rifts in volcanic arcs, usually during a period of relative volcanic quiescence. All but the late Paleozoic deposits of the Eagle Bay assemblage in the Kootenay Terrane are in allochthonous terranes that have accreted to North America. The deposits in the Sicker Group on Vancouver Island, including those at Buttle Lake, and those in the Tulsequah and Britannia areas are classified as Kuroko-type.

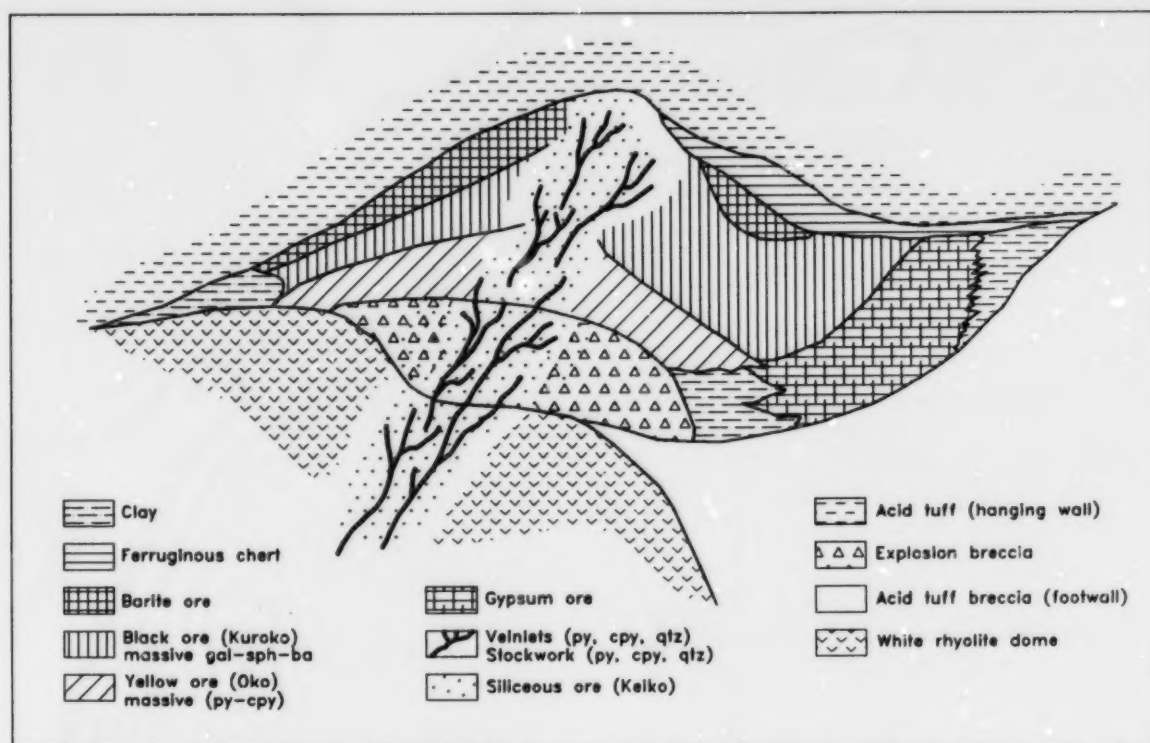


Figure 5-12. Cross-section of an ideal Kuroko deposit (after Sato, 1974 and Franklin et al., 1981).

A number of other deposits are more difficult to classify. Dolly Varden, Torbrit and North Star are silver-rich sphalerite-barite deposits in lower Jurassic Hazelton Group andesite tuffs. They are interpreted to be VMS deposits despite their unusual composition (Devlin, 1987). Their occurrence in possible arc volcanic rocks suggests a similarity with Kuroko-type deposits. The deposits of Eskay Creek include unusual stratabound massive sulphide layers with high silver and gold content (Table 5-3). They are spatially associated with other lenses that are rich in stibnite and realgar (Britton et al., 1990). They are described in more detail in a later section.

CU-ZN: CYPRUS-TYPE

Deposits that are classed as Cyprus-type include the Chu Chua deposit north of Kamloops, Lang Creek in northern British Columbia, a number of massive sulphide lenses at Anyox north of Prince Rupert and two small occurrences in the Bridge River Complex (Table 5-2). Their host successions and ages are varied. Chu Chua is within Mississippian-Permian mafic flows and tuffs of the Fennell Formation and Lang Creek is in the Sylvester allochthon, both part of the Slide Mountain Terrane. This terrane comprises oceanic, marginal-basin volcanic and sedimentary rocks that were accreted to North America as part of the Intermontane Superterrane.

Deposits of the Anyox camp are within a roof pendant of the Stikine Terrane in the Coast Crystalline Complex. Hostrocks are dominantly pillow basalts that may correlate with the Late Triassic Karmutsen Formation (Sharp, 1980). The Sunro deposit is within the Middle Eocene Metchosin ophiolite complex on southern Vancouver Island. It comprises a number of zones of essentially massive sulphides along a sheared contact between massive to amygdaloidal basalts and intrusive gabbro. It has also been interpreted as a shear-replacement deposit or a magmatic deposit.

Cyprus-type copper-zinc deposits in British Columbia have a number of common features. They comprise separate lenses of massive pyrite or pyrrhotite with chalcopyrite, sphalerite and commonly magnetite, underlain by prominent stockwork zones dominated by chlorite alteration, quartz veining and, at Chu Chua, talc and carbonate alteration. The Anyox deposits are at or near the contact of pillow basalts and overlying chert and argillite, indicative of quiescence at the end of a period of effusive volcanism.

Chu Chua (MINFILE 092P 140)

The Chu Chua property is located east of Chu Chua Mountain, 22 kilometres north-northeast of Barriere in south-central British Columbia. Massive

TABLE 5-2

Volcanogenic Massive Sulphide Deposits and Occurrences in British Columbia

Name	MINFILE No.	Type	Terrane	Host	Age
CAMBRIAN					
Goldstream area					
1 Goldstream	082M 141	Besshi	Kootenay	Lardeau	C
2 Montgomery	082M 085	Besshi	Kootenay	Lardeau	C
3 Standard	082M 090	Besshi	Kootenay	Lardeau	C
4 Brew	082M ?	Besshi	Kootenay	Lardeau	C
DEVONIAN					
Barriere area					
5 Twin Mtn.	082M 020	Kuroko(?)	Kootenay	Eagle Bay	D
6 Homestake	082M 025	Kuroko	Kootenay	Eagle Bay	D
7 Bay	082M 053	Kuroko	Kootenay	Eagle Bay	D
8 Joe	082M 054	Kuroko	Kootenay	Eagle Bay	D
9 Beca	082M 055	Kuroko	Kootenay	Eagle Bay	D
10 Birk Creek	082M 067, 60, 130, 131	Kuroko	Kootenay	Eagle Bay	D
11 May	082M 131	Kuroko	Kootenay	Eagle Bay	D
12 Rea	082M 191	Kuroko	Kootenay	Eagle Bay	D
13 Fortuna	092P 044	Kuroko	Kootenay	Eagle Bay	D
Vancouver Island					
14 Twin J		Kuroko	Wrangellia	Sicker	uD
Lenora	092B 001				
Tyee	092B 002				
Richard III	092B 003				
15 Lara		Kuroko	Wrangellia	Sicker	uD
Coronation Zone	092B 129				
Coronation Ext. Z.	092B 129				
Randy North Zone	092B 128				
Hangingwall Zone					
16 Anita	092B 037	Kuroko	Wrangellia	Sicker	uD
17 Sharon Copper	092B 040	Kuroko	Wrangellia	Sicker	uD
18 Water Power	092B 041	Kuroko	Wrangellia	Sicker	uD
19 Jane	092B 084	Kuroko	Wrangellia	Sicker	uD
20 Copper Canyon	092B 086, 4	Kuroko	Wrangellia	Sicker	uD
21 Breen Lake	092B 090	Kuroko	Wrangellia	Sicker	uD
22 Regina	092F 078	Kuroko	Wrangellia	Sicker	uD
23 Debbie	092F 125	Kuroko	Wrangellia	Sicker	uD
24 Thistle	092F 083	Kuroko	Wrangellia	Sicker	uD
25 Westmin					
Lynx	092F 071	Kuroko	Wrangellia	Sicker	uD
Myra	092F 072	Kuroko	Wrangellia	Sicker	uD
Price	092F 073	Kuroko	Wrangellia	Sicker	uD
H-W	092F 330	Kuroko	Wrangellia	Sicker	uD
PERMIAN-MISSISSIPPIAN					
26 Chu Chua	092P 140	Cyprus	Slide Mtn.	Fennel	M-P
27 Lang Creek	104P 008	Cyprus	Slide Mtn.	Sylvester	uPl
28 True Blue	082F 002	Besshi	Slide Mtn.	Milford	M-Pm
29 Packsack	103H 013	Kuroko	Taku (Wrangellia)		Pl
30 Horsefly	103H 014	Kuroko	Taku (Wrangellia)		Pl
31 Cimadoro	103F 052	Besshi(?)	Wrangellia	Sicker(?)	Pl(?)
32 Ecstall	103H 011	Kuroko	Taku (Wrangellia)		Pl
33 Scotia	103I 007	Kuroko	Taku (Wrangellia)		Pl
34 Pit	103H 066	Kuroko	Taku (Wrangellia)		Pl
35 Foremore	104G ?	Kuroko(?)	Stikinia	Stikine	D-M
Tulsequah area					
36 Tulsequah Chief	104K 061	Kuroko	Stikinia	Stikine	Pm
37 Big Bull	104K 008	Kuroko	Stikinia	Stikine	Pm
38 Maple Leaf	104K ?	Kuroko	Stikinia	Stikine	Pm
39 Ericksen-Ashby	104K 011	Kuroko	Stikinia	Stikine	Pm
40 Mary Mac	092J ?	Cyprus	Bridge R.	Bridge R.	Pm-Tr
41 New Discovery	092J 121	Cyprus	Bridge R.	Bridge R.	Pm-Tr
TRIASSIC					
42 Kutcho Creek	104I 060	Kuroko	Stikinia	Kutcho	uTr(?)
43 Windy Craggy	114P 002	Besshi	Alexander	Tats	uTr
44 Rime	114P 061	Besshi	Alexander	Tats	uTr
45 Rock and Roll	103H ?	Kuroko	Stikinia	Stuhini	uTr
Anyox area					
46 Hidden Creek	103P 021	Cyprus	Stikinia	Karmutzen	uTr
47 Bonanza	103P 023	Cyprus	Stikinia	Karmutzen	uTr
48 Double Ed	103P 025	Cyprus	Stikinia	Karmutzen	uTr
49 Redwing	103P 024	Cyprus	Stikinia	Karmutzen	uTr
50 Eden	103P 026	Cyprus	Stikinia	Karmutzen	uTr
51 Granduc	104B 021	Besshi	Stikinia	Stuhini	uTr
52 Sylvester K	082E 052	Kuroko	Quesnellia	Brooklyn	uTr
JURASSIC					
53 Dolly Varden	103P 088	Kuroko(?)	Stikinia	Hazelton	IJ
54 Torbrit	103P 191	Kuroko(?)	Stikinia	Hazelton	IJ
55 North Star	103P 189	Kuroko(?)	Stikinia	Hazelton	IJ
56 Eskay Creek	104B 009	(Kuroko)	Stikinia	Hazelton	mJ
57 Seneca	092H 013	Kuroko	Harrison	Harr. L.	mJ
CRETACEOUS					
58 Britannia	092G 003	Kuroko	Harrison	Gambier	K
59 Maggie	092G 036	Kuroko	Harrison	Gambier	K
60 McVicar	092G 006	Kuroko	Harrison	Gambier	K
61 Roy	092G 001	Kuroko	Harrison	Gambier	K
62 Hopkins	092G ?	Kuroko	Harrison	Gambier	K
USA					
63 Lockwood	Washington	Kuroko			K
64 Greens Creek	Alaska	Besshi	Stikinia	Stuhini	uTr

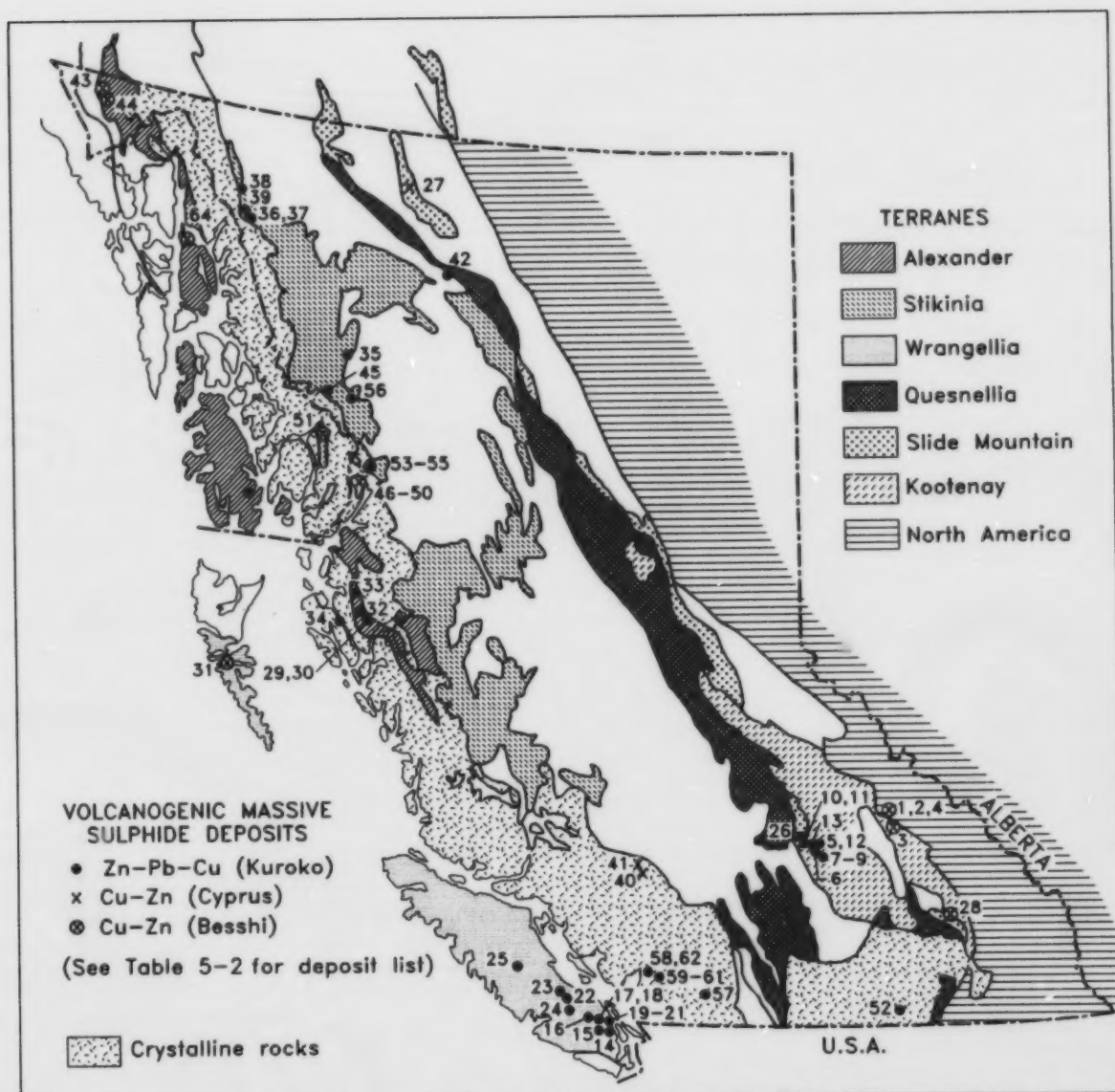


Figure 5-13. Distribution and classification of volcanogenic massive sulphide deposits in British Columbia. See Table 5-2 for list of deposits.

sulphides were discovered in 1978 by Craigmont Mines Limited by drilling a gossan containing slightly anomalous copper values. Drilling in 1978-79 outlined a deposit with reserves of approximately 2 million tonnes containing 2 per cent copper, 0.4 per cent zinc, 8 grams per tonne silver, 0.4 gram per tonne gold and 0.1 per cent cobalt. Reserves based on recent drilling by Minnova Inc. are approximately 1 million tonnes containing 2.97 per cent copper, 8 grams per tonne silver and 1 gram per tonne gold (Table 5-3). The geology of the Chu Chua property has been described by McMillan (1980), Vollo

(1981), Aggarwal and Nesbitt (1984) and Schiarizza and Preto (1987).

The deposit consists of two large and a number of smaller lenses of massive sulphides associated with pyritic chert, lenses of magnetite and magnetite-talc, and beneath one of the sulphide lenses, massive fine-grained talc. These zones are within pillow basalt of the Mississippian-Permian Fennell Formation. They strike north, dip vertically or steeply west, and stratigraphically overlie bleached, silicified and sparsely mineralized rock. Alteration minerals include talc, carbonate and chlorite.

TABLE 5-3

Volcanogenic Massive Sulphide Deposits — Reserves

No.	Name	Tonnes ¹	Cu (%)	Zn (%)	Pb (%)	Ag (g/t)	Au (g/t)
1	Goldstream	1.86	4.81	3.08	—	20.6	—
6	Homestake	0.915	0.55	4.00	2.5	240.0	—
	Kamad 7	0.220	0.54	7.32	6.19	69.19	7.36
12	Rea, L98	0.134	0.69	2.4	2.4	61.7	5.42
	Rea, Discovery	0.243	0.53	2.25	2.14	73.4	—
14a	Lenora	0.317	1.60	6.60	0.65	140.6	4.11
15	Lara	0.529	1.01	5.87	1.22	100.11	4.73
25	Westmin	12.1 ²	2.34	5.19	0.35	34.5	2.5
	Lynx	0.191	1.7	9.1	0.9	90.84	3.0
	Price	0.209	1.1	8.31	1.1	53.1	1.2
	H-W	10.138	2.0	3.5	0.3	30.4	2.1
26	Chu Chua	1.043	2.97	0.4	—	8.0	1.0
29	Packsack	2.7	0.5	0.2	0.01	34.0	0.3
32	Ecstall, S Lens	3.80	0.50	3.0	—	—	—
32	Ecstall, N Lens	3.10	0.80	2.0	—	17.1	0.5
33	Scotia	0.150	—	13.3	1.4	25.0	—
36	Tulsequah	5.26	1.6	7.03	1.31	100.5	2.74
39	Eriksen-Ashby	0.907	—	3.79	2.33	215.0	1.7
41	New Discovery	0.284	2.0	2.5	—	17.14	—
42	Kutcho	17.0	1.6	2.30	0.06	29.0	0.30
43	Windy Craggy ³	113.0	1.9	—	—	3.9	0.2
45	Rock and Roll	0.58	0.64	3.08	0.79	336.0	2.46
46	Hidden Creek	1.996	0.9	—	—	—	—
47	Bonanza	0.181	1.5	—	—	—	—
48	Double Ed	1.978	1.3	0.6	—	—	—
49	Redwing	0.181	1.84	—	—	29.5	—
51	Granduc	9.89	1.79	—	—	—	—
52	Sylvester K	0.05	—	—	—	—	—
53	Dolly Varden	1.134	—	0.80	0.50	325.0	—
54	Torbrit	0.360	—	—	—	260.0	—
55	North Star	0.128	—	3.0	2.0	401.0	—
56	Eskay	3.968 ⁴	—	—	—	998.4	26.0
	21A Deposit	0.968	—	—	—	126.8	9.6
57	Seneca	1.506 ⁵	0.63	3.57	0.15	41.14	0.82
		0.898	0.84	5.17	—	55.54	1.1
58	Britannia	1.413	1.90	—	—	—	—
60	McVicar	0.120	2.0	—	—	—	—
64	Greens Creek	3.2	0.45	9.7	3.9	816.0	6.17

¹ Reserves in million tonnes.² Includes reserves from the Lynx, Price and H-W orebodies.³ Reserves include 0.08 per cent Co.⁴ Geological reserves, excluding the 21A deposit.⁵ 1.506 metric tonnes of indicated reserves; 0.898 metric tonnes, measured.

NOTE: All reserve data are based on most recently available company data.

The massive sulphide deposits are composed of pyrite and chalcopyrite with minor sphalerite, cubanite, stannite-besterite solid solution, magnetite, quartz and calcite (Aggarwal and Nesbitt, 1984; Figure 5-14). The associated magnetite lenses contain some pyrite and chalcopyrite. Massive to locally brecciated chert layers contain minor disseminated pyrite and chalcopyrite; they are interpreted to be volcanic exhalite deposits. The massive talc unit contains minor magnetite; it has no textures indicative of replacement origin and is in sharp contact with other units, suggesting that it formed by direct

precipitation on the seafloor, similar to talc deposits associated with hydrothermal vents in the Guaymas Basin (Lonsdale *et al.*, 1980).

Basaltic rocks of the Fennell Formation are not typical oceanic tholeiites as the composition of relict augites indicates an original alkalic or transitional composition. This suggests that at least part of the Fennell Formation may have formed as volcanic islands in an intraplate environment (Aggarwal, 1982; Aggarwal *et al.*, 1984). This setting is unusual for VMS deposits. It is more likely that the Fennell Formation and contained VMS deposits formed in

TABLE 5-4

Volcanogenic Massive Sulphide Deposits — Production Data¹

No.	Name	Tonnes	Cu	Zn	Pb	Ag	Au
1	Goldstream	427 886	11 849	505	—	3 820	—
6	Homestake	4 296	9	203	141	8 751	11.3
14	Lenora ³	119 831 ²	3 595	1 926	165	10 722	386.1
	Tyee	152 668 ²	5 841	—	—	13 725	762.5
	Richard III	4 903 ²	114	—	—	523	22.8
24	Thistle	6 283 ²	309	—	—	66	85.9
25	Westmin ^{3,4}	10 392 097	176 423	558 384	56 795	636 409	16 418.0
36	Tulsequah ^{3,5}	933 609	12 341	56 559	15 214	105 774	2 931.7
46	Hidden Creek	21 725 524 ²	321 546	—	—	206 309	3 772.8
47	Bonanza	655 656	14 300	—	—	8 748	86.6
51	Granduc	15 173 140 ²	190 144	—	—	124 049	2 000.1
53	Dolly Varden	33 434	0.2	—	0.9	42 451	—
54	Torbrit	1 251 339	—	283	4 868	579 956	3.4
55	North Star	101 ²	—	—	—	88	—
57	Seneca	260 ²	3	18	—	30	0.5
58	Britannia ³	47 402 534	516 960	125 291	15 563	180 846	15 350.6

¹ Copper, zinc and lead data in 1000 kg; silver and gold in kg (to 1989 inclusive).² Tonnes mined, not milled.³ Deposit also produced cadmium.⁴ Includes production from Lynx, Myra and H-W deposits.⁵ Includes production from Big Bull, 1951–1956.

NOTE: Data from B.C. Geological Survey Branch MINFILE.

marginal basins, possibly back-arc basins, in relatively close proximity to the Eagle Bay assemblage of the pericratonic Kootenay Terrane (Schiarezza and Preto, 1987).

Anyox (MINFILE 103P 021 to 25)

Deposits in the Anyox district north of Prince Rupert were major producers of copper between 1914 and 1936 (Nelson, 1935; 1948). Approximately 22 million tonnes of ore were mined from the largest of the deposits, the Hidden Creek orebody, producing 322 000 tonnes of copper, 206 tonnes of silver and 3.8 tonnes of gold (Table 5-4). The large reserve tonnage reported (Table 5-3) is primarily for a quartz-vein stockwork zone.

The massive sulphide deposits occur at or near a conformable contact of tholeiitic basalts and an overlying argillite succession, both of upper Triassic age (Figure 5-15). They are composed mainly of pyrite with lesser amounts of pyrrhotite, chalcopyrite and sphalerite (Sharp, 1980). Footwall rocks comprise a thick pillow basalt sequence, overlain by basaltic tuff interbedded with chert, and a crudely bedded chert unit that is associated with the largest sulphide masses. Both the tuff and chert units are thickest beneath the sulphide masses; the chert can be traced for several kilometres away from the Hidden Creek area.

The footwall rocks are variably altered with silica, sericite and chlorite and locally cut by well-defined quartz-sulphide stringer zones. The basaltic tuff unit beneath the Hidden Creek deposit contains a few small, massive pyrrhotite lenses and disseminated to

bedded pyrrhotite with minor pyrite and chalcopyrite. The chert lens also contains disseminated sulphides, small, massive sulphide lenses, and sericite, chlorite and minor magnetite. The stringer zones are in chloritized rocks with alteration increasing in intensity toward the base of the sulphide layers. Locally, footwall basalts are weakly albitized, indicative of sodium metasomatism.

The deposits at Anyox are within pillow basalts and tuffs, associated with exhalite chert, and overlain by argillites. These volcanic rocks are low-potassium tholeiites, similar in age and chemistry to upper Triassic volcanic rocks of the Karmutsen Formation in Wrangellia, and dissimilar to volcanic and sedimentary rocks of the Alexander and Stikine terranes (MacIntyre, 1986). The MORB characteristics of volcanic rocks hosting Anyox deposits, associated deep-water lithologies, and overlying fine-grained sedimentary successions indicates deposition in an oceanic environment at the end of a period of effusive volcanism.

CU-ZN: BESSHI-TYPE

Besshi-type copper-zinc deposits in British Columbia (Table 5-2, Figure 5-13) include the lower Paleozoic Goldstream deposit north of Revelstoke, the True Blue deposit on the west side of Kootenay Lake and the Granduc mine northwest of Stewart. Windy-Craggy, located in the St. Elias Mountains in northwestern British Columbia also has some similarities with this class of deposit. Both the Granduc and Windy-Craggy deposits are in Late Triassic rocks.

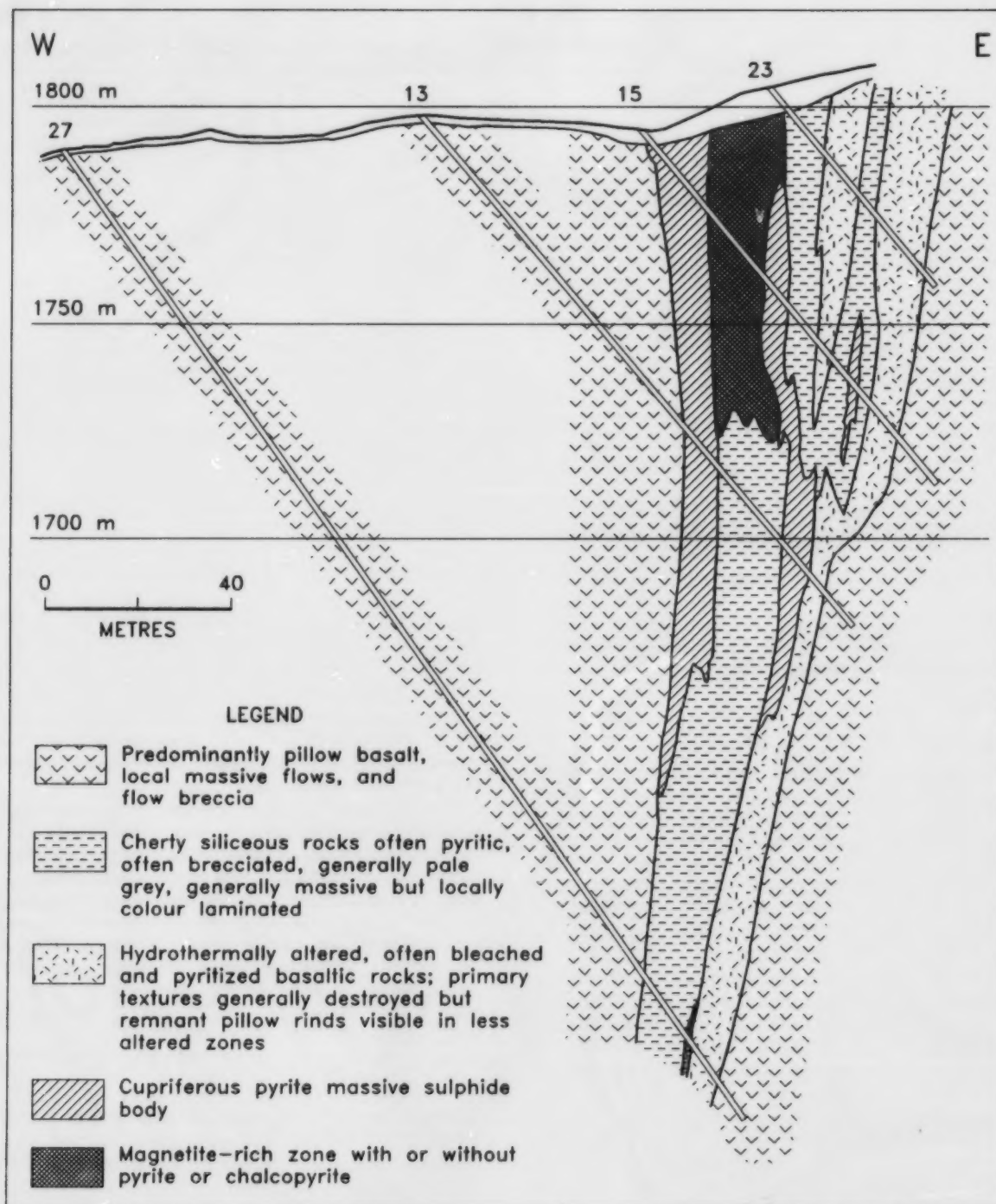


Figure 5-14. Cross-section through the Chu Chua deposit (after McMillan, 1980; in Schriazzia and Preto, 1987).

These deposits all occur within mafic volcanic rocks or associated clastic sedimentary rocks. In contrast with the typical MORB or tholeiitic character of hostrocks of the Cyprus-type deposits, Besshi-type deposits are generally in calcalkaline rocks. The associated sedimentary succession is also different, commonly including coarser clastic and platformal carbonates indicative of deposition close to continental margins. Hence, their inferred tectonic setting is in rifted marginal basins or back-arc basins.

Although the type Besshi deposit does not have well-documented zoning patterns, alteration envelopes or footwall stockwork zones, British Columbia examples have some of these features. Mineralogical and metal zoning is well displayed at Windy Craggy and Goldstream. Goldstream has a broad semiconformable alteration zone in its stratigraphic footwall and Windy Craggy has a prominent footwall stringer-sulphide zone. The intense deformation and associated regional metamorphism characteristic of many Besshi deposits have probably obliterated these primary features.

Besshi deposits are commonly thin, tabular lenses composed primarily of pyrite or pyrrhotite, with chalcopyrite and sphalerite. Some contain high concentrations of gold and cobalt. As a number of terranes in British Columbia are dominated by calcalkaline volcanism and have considerable input of clastic sedimentary rocks, these deposits are a viable exploration target. However, their common lack of extensive well-defined alteration envelopes and occurrence at variable horizons make them a difficult exploration target.

Goldstream (MINFILE 082M 141)

The Goldstream deposit was discovered beneath a gossan in 1973 and optioned by Noranda Exploration Company Limited in 1974. Fifty drillholes outlined a deposit with reserves of 3.2 million tonnes containing 4.5 per cent copper, 3.1 per cent zinc and 20 grams per tonne silver. Mining in 1983 and 1984 produced 11 849 800 kilograms of copper, 505 000 kilograms of zinc and 3820 kilograms of silver from approximately 428 000 tonnes of ore (Table 5-4). Goldstream has recently been acquired by Bethlehem Resources Corporation and Goldneve Resources Inc. and is now back in production.

The Goldstream area is underlain by Late Proterozoic and Early Paleozoic metasedimentary and metavolcanic rocks of the Kootenay Terrane (Höy, 1979; Höy *et al.*, 1984). Immediate hostrocks are correlated with the Index Formation, the basal part of the Lardeau Group. These rocks are dominantly dark calcareous phyllites and basic metavolcanic rocks. They overlie a succession of pelitic phyllite and quartzite that has been tentatively correlated with platformal rocks of the Eocambrian Hamill Group exposed farther south in the Kootenay Arc.

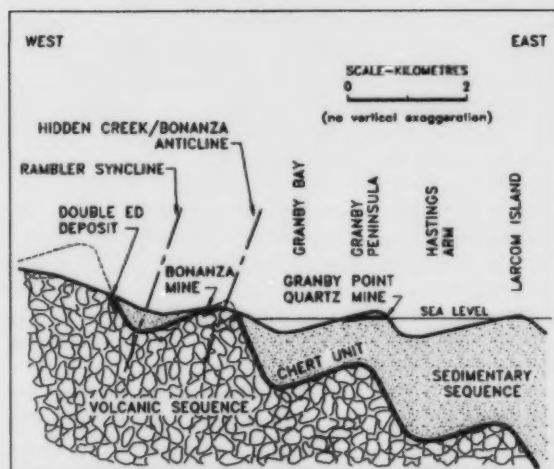


Figure 5-15. Schematic east-west cross-section in the southeastern Anyox pendant (from Alldrick, 1986).

Metavolcanic rocks include massive, fine to medium-grained greenstones that locally contain remnant pillow structures. Green chloritic phyllite is interpreted to be mafic tuff units. These rocks are interlayered with the dark calcareous phyllite that hosts the Goldstream deposit. Farther south, near the Standard copper-zinc massive sulphide deposit, coarse-grained ultramafic pods underlie the basalts.

The Goldstream deposit is a thin conformable sheet of massive sulphides in sericitic quartzite and calcareous and chloritic phyllite (Figure 5-16). It averages between 1 and 3 metres in thickness, has a strike length of at least 400 metres and a down-plunge extension of greater than 1200 metres. Contacts with hangingwall and footwall rocks vary from sharp to gradational; in general, however, the structural hangingwall is more gradational and this, combined with regional structural interpretations, indicates that the deposit and its host succession are inverted.

Sulphides consist mainly of pyrrhotite, chalcopyrite and sphalerite with numerous subrounded inclusions of quartz, phyllite and carbonate. Gneissic sulphide textures are common, particularly along the margins of the sulphide layer. Metal grades have a simple and regular pattern with increasing values towards the central, thicker parts of the layer. However, a pronounced lateral Zn/Zn+Cu zoning is apparent, with copper increasing toward the west (Figure 5-17). It is suggested (Höy *et al.*, 1984) that this zonation reflects an original depositional configuration, either an original lateral zonation (Figure 5-18a) or shearing of a massive sulphide lens with a high-grade core but with an original vertical zoning (Figure 5-18b). Alternatively, it is possible that the zoning results from preferential migration of chalcopyrite towards the western side of the orebody.

during metamorphism and deformation (Lindsay Bottomer, personal communication, 1991).

The massive sulphide layer is enclosed in an envelope of pale, siliceous chlorite and sericitic phyllite (Unit 4) that grades to fine-grained sericite-chlorite quartzite. Although Unit 4 may, in part, represent epiclastic accumulations, it also may include a siliceous exhalite component. It is structurally overlain by Unit 3, informally called the garnet zone, which consists of thin, dark chert layers with spessartine garnets, dark chloritic layers, and locally abundant pyrrhotite. The garnet layer is interpreted to be a manganiferous, iron-rich chert exhalite that formed just prior to massive sulphide deposition. Magnesium-chlorite and associated sulphides are remnants of an original footwall alteration zone. Chlorite, carbonate, quartz and pyrrhotite, ubiquitous throughout Unit 2 (Figure 5-18), may be evidence of a much larger semi-conformable alteration zone in the original stratigraphic footwall of the Goldstream deposit.

In summary, massive sulphide accumulation is associated with siliceous exhalites, a manganiferous-silica exhalite and silica, chlorite and minor sericite alteration. The deposit is inverted and hence this alteration, particularly the pronounced magnesium-chlorite sulphide alteration, is abundant in the structural hangingwall of the lens.

A number of other similar copper-zinc deposits occur in correlative rocks south of Goldstream. The Standard deposit consists of a series of thin, generally discontinuous chalcopyrite-pyrite-pyrrhotite lenses with associated disseminated sulphides in greenstone and dark calcareous phyllite. The Montgomery showings are a series of lenses of massive and disseminated sulphides in micaceous chloritic schist (mafic tuff) and sericitic quartzite. The lenses are up to 3 metres thick and are composed of massive pyrrhotite with minor pyrite, chalcopyrite, sphalerite and trace galena.

Rocks of the Goldstream area are interpreted to have been deposited near the western limit of exposed miogeoclinal rocks (Höy, 1979). The change from deposition of clean, massive terrigenous quartzites interbedded with pelites, to impure carbonate and dark carbonaceous shale indicates rapid subsidence. Interbedded coarse clastics, pillow basalts and mafic tuffs suggest deposition in a rifted basin. This basin may have formed in response to crustal extension along the western margin of North America in Early Paleozoic time.

Windy Craggy (MINFILE 114P 002)

The Windy Craggy deposit, located in the extreme northwest corner of British Columbia, was discovered in 1958 by Frobisher Limited (Falconbridge

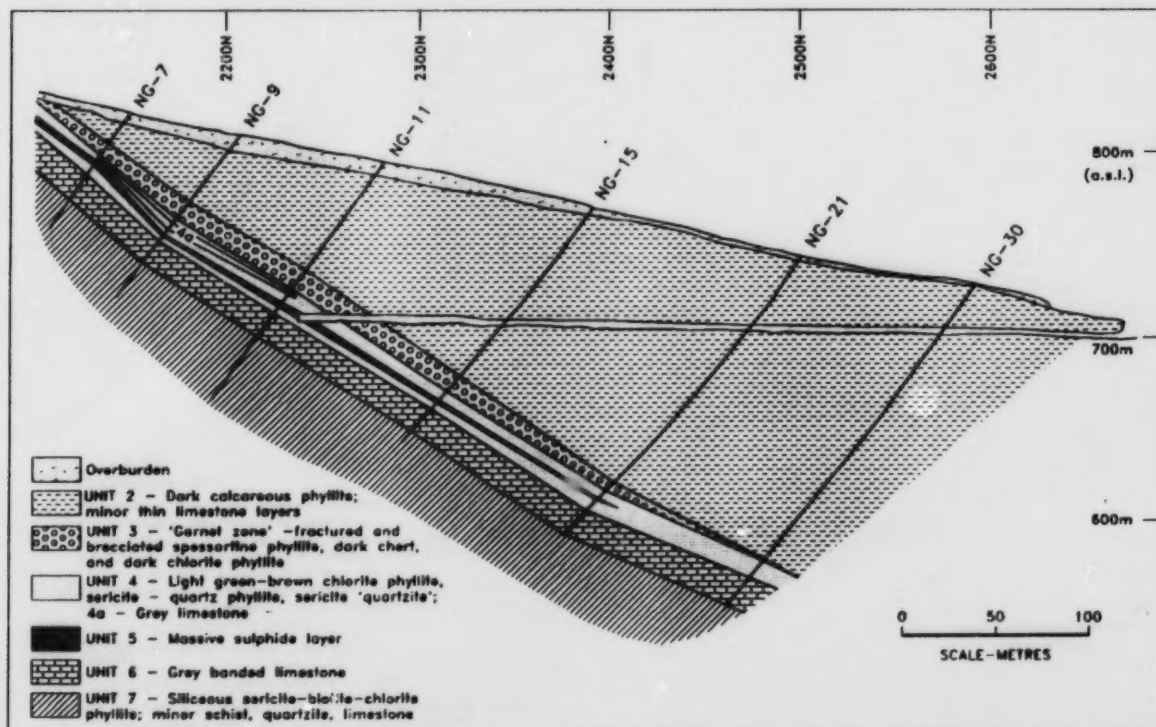


Figure 5-16. A north-south vertical section through the Goldstream deposit, viewed from the east (from Höy et al., 1984).

Mines Ltd). In 1987, Geddes Resources Ltd., the current operators, commenced development of an adit that would extend to a gold-rich part of the deposit. Underground work continues on the property in preparation for production. The deposit is one of the world's largest massive sulphide deposits, with reserves of greater than 210 million tonnes containing about 1.6 per cent copper, 0.2 gram per tonne gold and 0.09 per cent cobalt. The following description is summarized from papers by Peter (1989) and MacIntyre (1984, 1985).

The Windy Craggy area is within the Alexander Terrane of the Insular Belt. The stratigraphic succession in the vicinity of the deposit consists of a lower unit of mafic to intermediate flows and volcanic breccia, overlain by calcareous and carbonaceous siltstones, greywackes, carbonates and intermediate tuffs and flows (MacIntyre, 1983). The age of this succession is Late Triassic, based on conodont assemblages. The deposit is at the contact of an altered pillow basalt unit with minor intercalations of chert and limy argillite and an overlying succession of limy siltstone and argillite with interbedded tuffs and flows (Figure 5-19). Interlaminated chert, carbonate (calcite, siderite and ankerite) and sulphides occur associated with the massive sulphides.

Several phases of intense deformation have affected these rocks. Isoclinal first-phase folds trend northwest. These are superimposed by more open north to northeast-trending folds.

Two main sulphide bodies have been identified, the North and the South which lie along a strike length of 500 metres. The North body is folded into a large, upright syncline that plunges steeply to the northwest (Figure 5-20) whereas the South body is a southeast-plunging monocline.

The massive sulphides comprise three main types (Peter, 1989): pyrrhotite with lesser chalcopyrite, pyrite with lesser chalcopyrite, and pyrrhotite and pyrite with lesser chalcopyrite and magnetite. Other metallic minerals include sphalerite, arsenopyrite, galena, marcasite, cubanite and cobaltite. Gangue minerals include quartz, chlorite, calcite, ankerite, siderite, stilpnomelane, biotite and graphite. The massive sulphides may be zoned from massive pyrrhotite nearest the footwall to a massive pyrite zone at the stratigraphic top.

These sulphide bodies have well-developed stockwork stringer zones in their stratigraphic footwall. They consist of veins and veinlets of carbonate and quartz with pyrrhotite, minor chalcopyrite and rare pyrite in intensely chloritized and locally brecciated rocks. Locally, the stratigraphic footwall rocks are also intensely silicified and bleached. Less intensely altered rocks include pervasively chloritized mafic flows and tuffs.

Of considerable economic interest at Windy Craggy is a brecciated siliceous zone that contains very high gold values. Diamond-drill Hole 84-13

intersected 61.3 metres that assayed 4.46 grams per tonne gold and 0.62 per cent copper. A 5.5-metre section within this interval assayed 11.66 grams per tonne gold, 3.09 grams per tonne silver and 0.98 per cent copper. The zone is interpreted to be a section of hydrothermally altered argillite and volcanic rocks.

Windy Craggy is a copper-zinc volcanogenic massive sulphide deposit in mafic volcanic rocks of Late Triassic age. Although it has features similar to Cyprus-type deposits, the calcalkaline nature of the

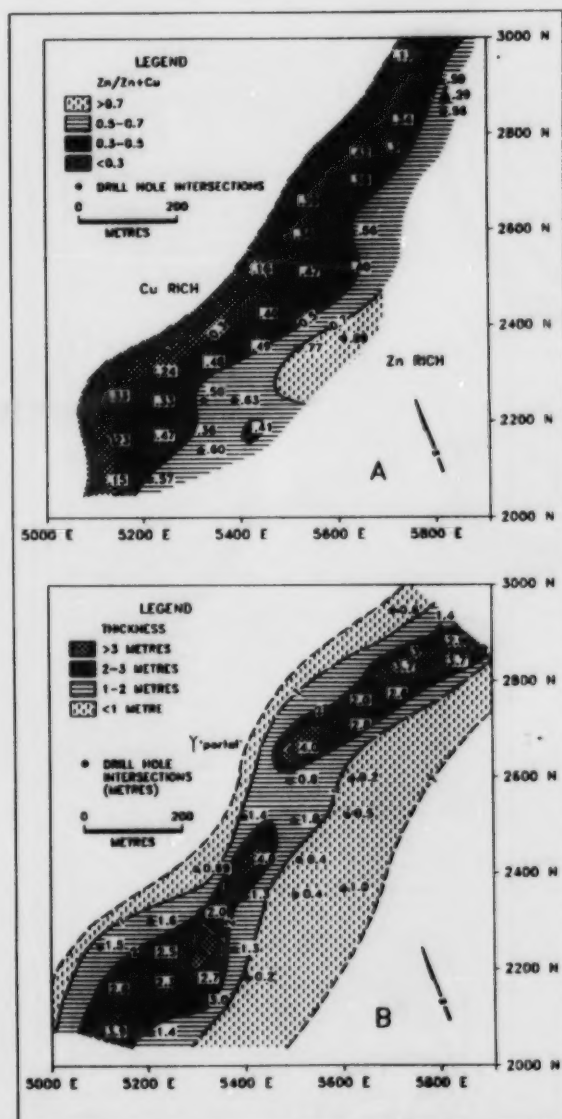


Figure 5-17. (a) Weighted Zn/(Zn+Cu) ratios in the Goldstream massive sulphide layer; (b) Isopach map of massive sulphide layer (from Höy et al., 1984).

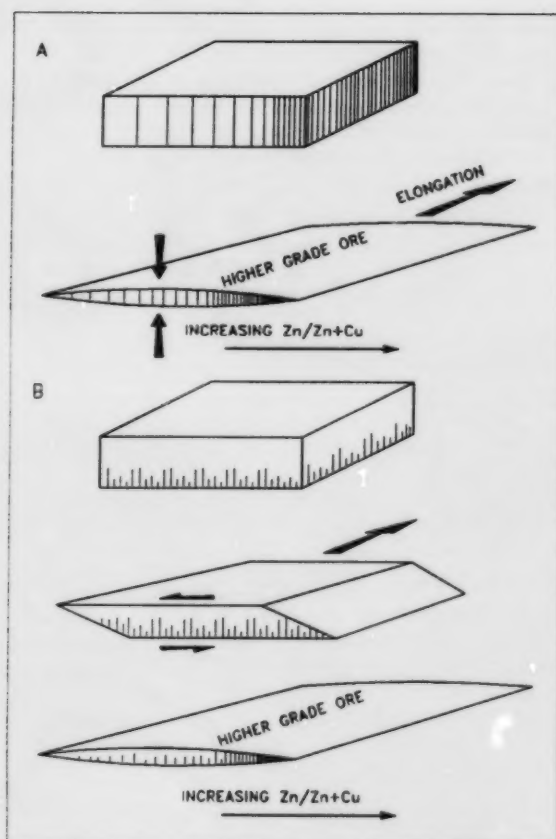


Figure 5-18. Two models that illustrate flattening and elongation of a massive sulphide lens during extreme deformation. Both models can account for the pronounced lateral Zn/Zn+Cu zonation, the retention of a high-grade core, and the thickening in the central part of the layer. Model A assumes an original metal zonation; model B produces lateral zonation by simple shearing of a lens that was originally zoned vertically.

mafic volcanics (MacIntyre, 1986) and its association with a considerable succession of clastic rocks suggests that it more closely resembles Besshi-type deposits. MacIntyre (1984) compares its setting with the Guaymas Basin in the Gulf of California – rifting associated with the earliest stages of separation of continental masses.

ZN-PB-CU: KUROKO-TYPE

Deposits similar to the Kuroko-type are the most common VMS occurrences in British Columbia. They include numerous deposits in the Late Devonian Eagle Bay assemblage northeast of Kamloops, Late Devonian deposits in the Sicker Group on Vancouver Island, the Tulsequah Chief and Big Bull deposits in northwestern British Columbia, Kutcho Creek in Late Triassic rocks of the Stikine Terrane in

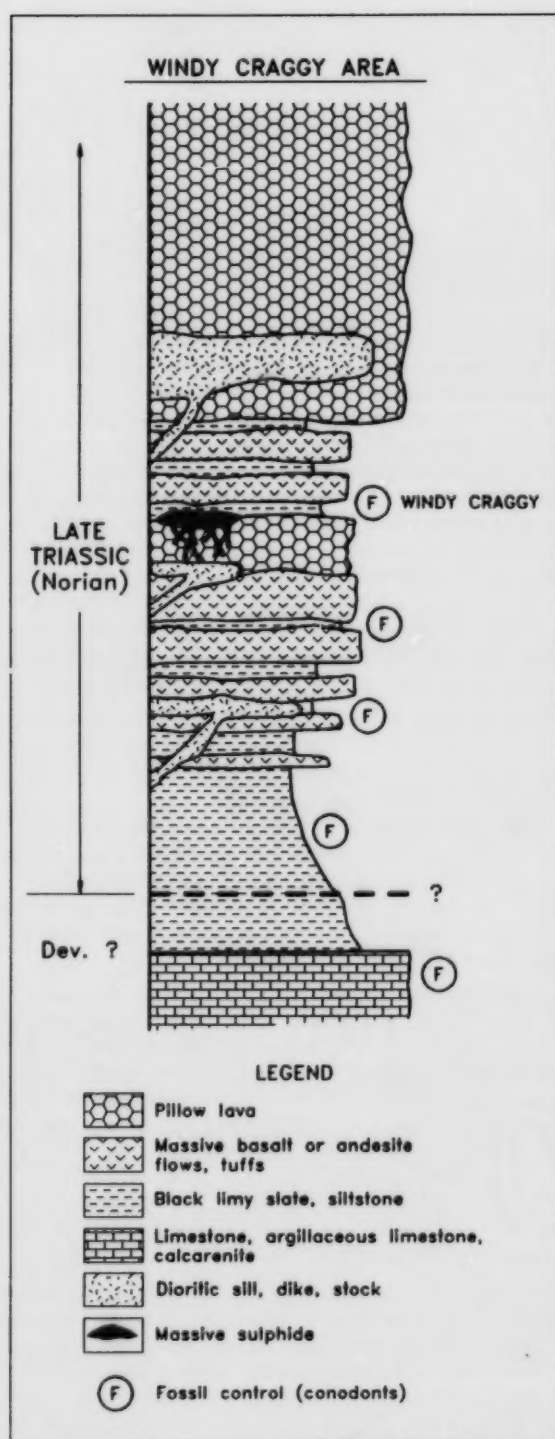


Figure 5-19. Generalized stratigraphic column for the Windy Craggy area showing approximate position of mineral occurrences (from MacIntyre and Schroeter, 1985).

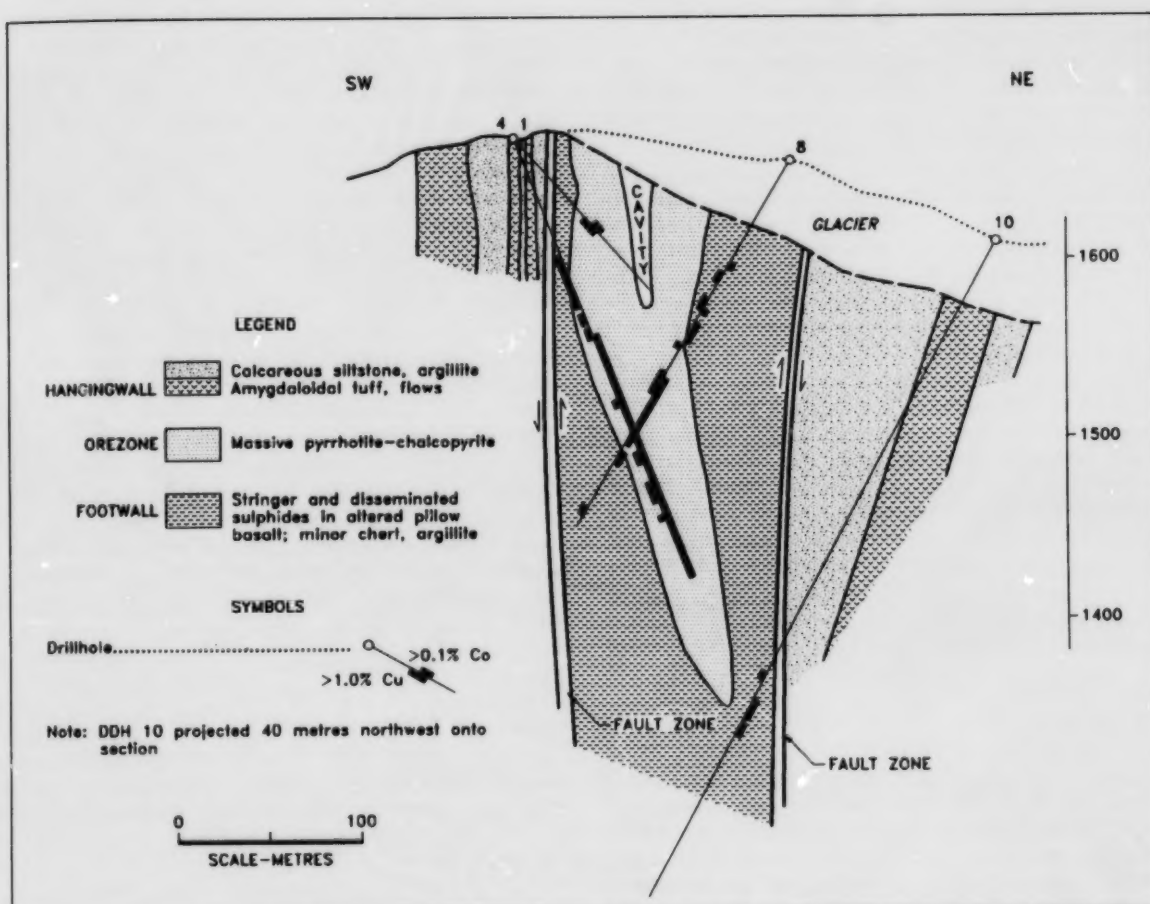


Figure 5-20. Interpretive drill section, Windy Craggy (from MacIntyre, 1984).

the north-central part of the province, and Britannia and Seneca in roof pendants in the Coast crystalline belt north and east of Vancouver (Figure 5-13).

Hostrocks for these deposits are bimodal, calc-alkaline volcanic rocks that typically formed during a rifting event during constructive development of an island-arc complex. They are most commonly recognized by their polymetallic nature, their close association with dacite or rhyolite and common association with sulphate facies.

Buttle Lake camp

Two ore deposits, the H-W and Lynx, are currently being mined by Westmin Mines Ltd. in the Buttle Lake area southwest of Campbell River on Vancouver Island (Figure 5-13). A third deposit, the Myra, closed in late 1985 due to depletion of reserves. The Upper Price zone, with reserves of 209 500 tonnes containing 1.1 per cent copper, 8.31 per cent zinc, 1.07 per cent lead, 53 grams per tonne silver and 1.2 grams per tonne gold has not been put into produc-

tion (Table 5-3). Total production, since 1967, is summarized in Table 5-4.

The Buttle Lake deposits consist of a number of massive sulphide lenses within felsic volcanic rocks in the Late Paleozoic Sicker Group (Walker, 1985; Walker and Pearson, 1985; Juras and Pearson, 1990). The Sicker Group has been subdivided into four formations, the Late Devonian (or older) Price Formation, the Late Devonian Myra Formation, the Early Mississippian Thelwood Formation and the Pennsylvanian or Mississippian Flower Ridge Formation (Juras, 1987). The Price and Myra formations record cyclical volcanism, with early mafic to intermediate volcanism during constructive arc development, followed by rifting and associated hydrothermal alteration, sulphide mineralization and felsic arc volcanism, then mafic to ultramafic arc volcanism and finally volcanogenic sedimentation (Juras, 1987). The H-W deposits are within felsic volcanic rocks of an early cycle, whereas the Lynx, Myra and Price deposits are in a later felsic succession.

The Price Formation or footwall H-W andesite comprises greater than 300 metres of dominantly

massive to pillowed andesite flows and flow breccias with minor intercalated pyroclastic rocks. It is overlain by the Myra Formation, a heterogeneous succession of dominantly pyroclastic and flow units that hosts the sulphide deposits and is locally referred to as the Mine sequence.

The lowermost unit of the Myra Formation, the H-W horizon comprises dacite to rhyolite flows, pyroclastic deposits, argillite and the H-W deposit. Subaqueous pyroclastic flow deposits within the H-W horizon are widely distributed whereas debris flow deposits are areally restricted to a central region. Basaltic andesite to andesite flows and breccias, the hanging wall H-W andesite, overlies the H-W horizon. A series of submarine volcanoclastic debris flows with variable compositions but containing prominent massive sulphide clasts are included in the Ore-clast breccia unit. An overlying volcanoclastic unit, comprising bedded lapilli-tuff and coarse to fine tuff, tuff breccia and minor subaqueous pyroclastic flow deposits occurs throughout the area and marks the end of the first volcanic cycle.

The Upper dacite, 5E andesite and North dacite, record approximately contemporaneous eruptive events throughout the mine area (Juras and Pearson, 1990). The Lynx, Myra and Price deposits are within massive to bedded, fine to coarse quartz-feldspar rhyolite tuff and lapilli tuff. A thin, laminated chert unit occurs locally within these tuff units. Thin ultramafic flows and flow breccias (G-flow unit) overlie the Lynx-Myra-Price horizon. They are overlain by a volcanoclastic succession consisting of bedded tuff, lapilli-tuff, massive coarse lapilli tuff and tuff-breccia. Locally, maroon tuff beds indicate shallow marine to subaerial deposition.

The stratigraphically highest rhyolite horizon in the Myra Formation or Mine sequence is referred to as the Upper rhyolite unit. It comprises a siliceous argillite-chert member, commonly overlain by bedded crystal tuff and lapilli tuff. The Upper rhyolite unit is overlain by basaltic hydroclastite and pyroclastic deposits with minor flows and flow breccias.

The Thelwood Formation (Sharp banded tuff) comprises up to 500 metres of siliceous tuffaceous sediments, subaqueous pyroclastic flow deposits and mafic sills (Juras, 1987). The Flower Ridge Formation, the top of the exposed Sicker succession, consists mainly of amygdaloidal basaltic lapilli-tuff, tuff breccia and pyroclastic breccia.

The H-W deposit consists of a number of lenses of massive sulphides, referred to as the Main zone, North lenses and Upper zones, that are commonly located at the base of the H-W horizon (Figure 5-21). The lenses comprise fine-grained massive to thin bedded pyrite, sphalerite and chalcopyrite with lesser bornite, tennantite and galena. Non-sulphide minerals include barite, quartz and sericite.

The Main zone, the largest of the H-W lenses, is approximately 1200 metres long, 500 metres wide and 3 to 80 metres thick (Walker, 1985; Juras and

Pearson, 1990). It is zoned, with a pyrite-rich central zone that contains chalcopyrite and sphalerite-rich areas to a barite-rich, pyrite-poor fringe zone with significant sphalerite, chalcopyrite, galena and bornite. The mineral zoning is reflected in Cu:Zn ratios with generally a copper-rich central zone and a zinc-rich fringe zone. Gold is distributed fairly uniformly throughout the deposits (Walker, 1985). The sulphide deposits of the Lynx-Myra-Price horizon are generally located on or near the upper contact of the horizon (Figure 5-21). They are composed of banded sphalerite, chalcopyrite, pyrite, galena and minor tennantite with barite, quartz and sericite.

Alteration zones occur in andesites beneath both the H-W deposit and the Southwall zone of the Lynx mine. The zones are characterized by intense silicification and sericitization with locally complete replacement to quartz-sericite-pyrite-(chlorite) assemblages with variable amounts of pyrite. Chlorite alteration generally occurs marginal to this intense alteration zone. The alteration zone beneath the H-W deposit is flanked by a zone of moderate to strong albitization and silicification, producing an assemblage of albite, quartz and sericite.

In summary, the deposits of the Buttle Lake area are typical of many polymetallic or Kuroko-type deposits. They are within felsic pyroclastic rocks, have well developed alteration zones beneath them and are interpreted to have formed during rifting of a mature island arc succession. Other deposits within the Late Paleozoic Sicker Group, including those of the Twin J mine and the Lara, are in similar successions.

Rea (MINFILE 082M 191)

The Rea deposit was discovered in 1983 and optioned first to Rea Gold Corporation, then to Corporation Falconbridge Copper (now Minnova Inc.). It has undergone extensive exploration including trenching, diamond drilling and underground development. A number of small massive sulphide and barite lenses are recognized; these are distinct from the essentially quartz-hosted Samatsum deposit. The Rea deposit is within a thick sequence of Late Devonian intermediate to felsic volcanic and volcanoclastic rocks (Unit EBF) of the Eagle Bay assemblage (Schiarizza and Preto, 1987). The immediate hostrocks are an altered sequence of dominantly mafic tuffs overlain by argillite, grit and minor mafic tuff (Höy and Goutier, 1986). The succession is inverted; hence, the "footwall alteration zone" or "stockwork feeder zone" now forms the hangingwall of the lenses.

The oldest unit within the deposit area comprises ash, crystal and lapilli tuffs (Unit 1) that lie at the structural top of the succession (Figure 5-22). Thin chert bands and an increase in sericite content are noticeable towards its contact with Unit 2. Unit 1 has been extensively altered to an assemblage of chlorite, ankerite, albite, sericite, pyrite and epidote.

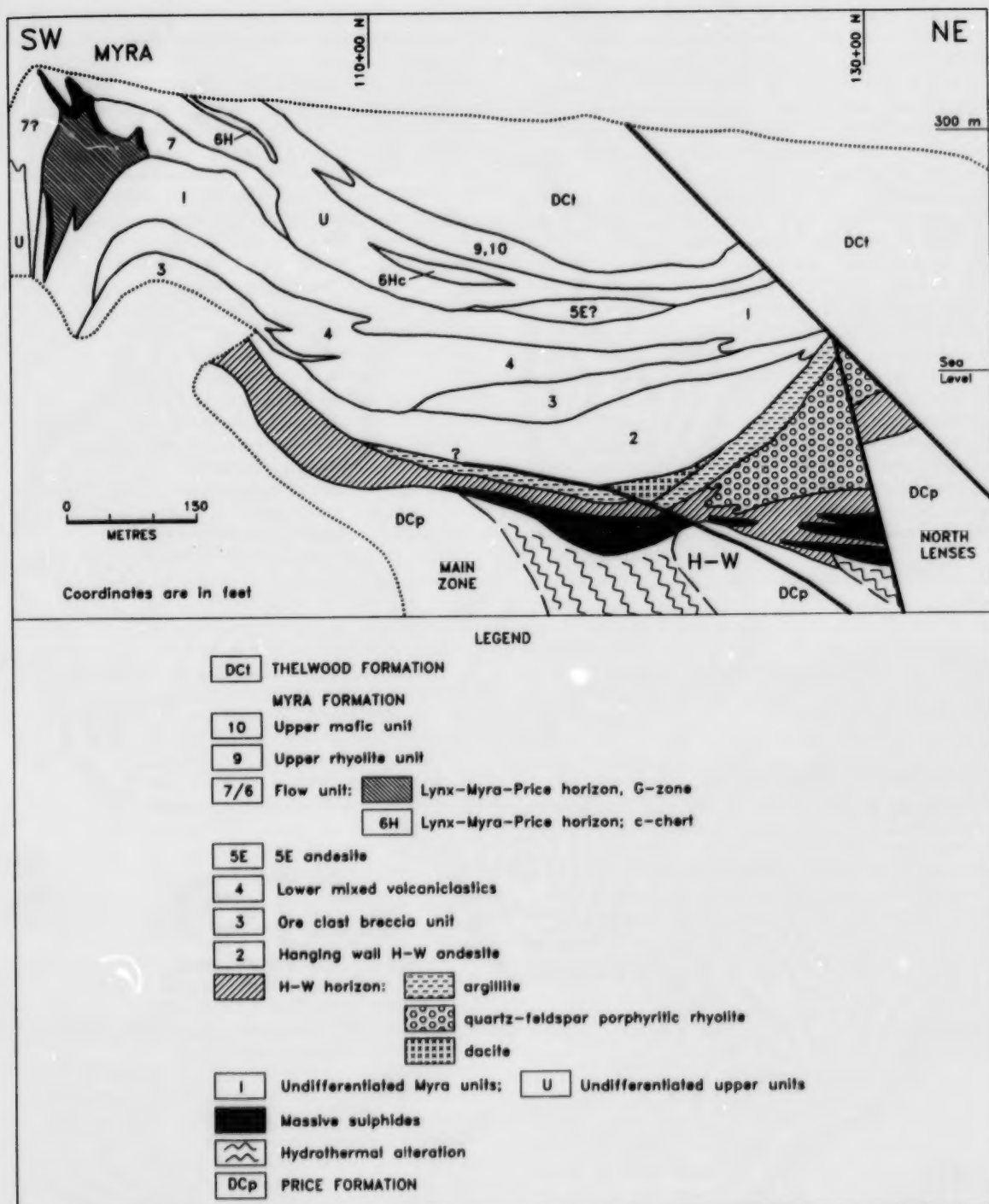


Figure 5-21. Composite geology along the H-W-Myra section (24+00E), (after Walker, 1985).

Trace and major element chemistry indicates that these rocks were alkali basaltic in composition (Höy, 1987).

Unit 2 is the stockwork zone of the massive sulphide lenses. It includes extensively altered mafic tuffs, chert layers and possibly a minor felsic tuff component. The intense alteration is marked by a dramatic increase in quartz and sericite (Figure 5-23), reflecting addition of silica and potassium and corresponding decrease in magnesium, calcium and sodium (Figure 5-24). Silicification is present in the form of veins, thin to relatively thick chert "layers", discontinuous chert lamellae and fragmental chert. It is accompanied by vein and disseminated pyrite, and ubiquitous sericite. These stockwork alteration assemblages are schematically illustrated in Figure 5-23b. Note also minor and local sodic enrichment (albite) near the top of Unit 2 and minor, but persistent sericite alteration above the sulphide lens as well. Trace element analyses of Unit 2 indicate that originally it was dominantly mafic tuffs (Höy, 1987). The intense alteration, overprinted by regional deformation and metamorphism, has produced a quartz-sericite schist that resembles a metamorphosed felsic volcanic unit.

A number of sulphide lenses are known at Rea Gold. The R8 lens has a relatively sharp contact with altered stockwork rocks and grades stratigraphically up into massive barite that contains variable amounts of disseminated sulphides. At its fringes, however, it is in sharp contact with overlying tuffaceous muds of Unit 5. The L100 lens has a surface strike length of approximately 50 metres and a down-dip projection of at least 120 metres. It has a thick zone of intense silica alteration stratigraphically beneath it and is abruptly overlain by mafic tuffs. It does not have a barite "cap". A third massive sulphide lens between the R8 and L100 lenses was intersected by diamond drilling. Sulphide mineralogy in the lenses includes pyrite, arsenopyrite, galena, chalcopyrite and tetrahedrite-tennantite. Gold occurs in the massive sulphides but is also found in the barite and in the "footwall" stockwork zone.

The alkalic nature of host rocks at Rea Gold is unusual for volcanogenic massive sulphide deposits. Rocks underlying Rea Gold, including host rocks of the Homestake deposits, are calcalkaline, more typical of arc volcanism. It is suggested that the Rea succession represents deposition in a rift developed in a mature island arc. A thick accumulation of overlying clastic rocks indicates that volcanism ceased, probably because the rift failed.

Homestake (MINFILE 082M 025)

The Homestake deposit was mined intermittently between 1926 and 1941, producing approximately 11.3 kilograms of gold, 8751 kilograms of silver, 9140 kilograms of copper, 141 300 kilograms of lead and 203 300 kilograms of zinc from 4 300

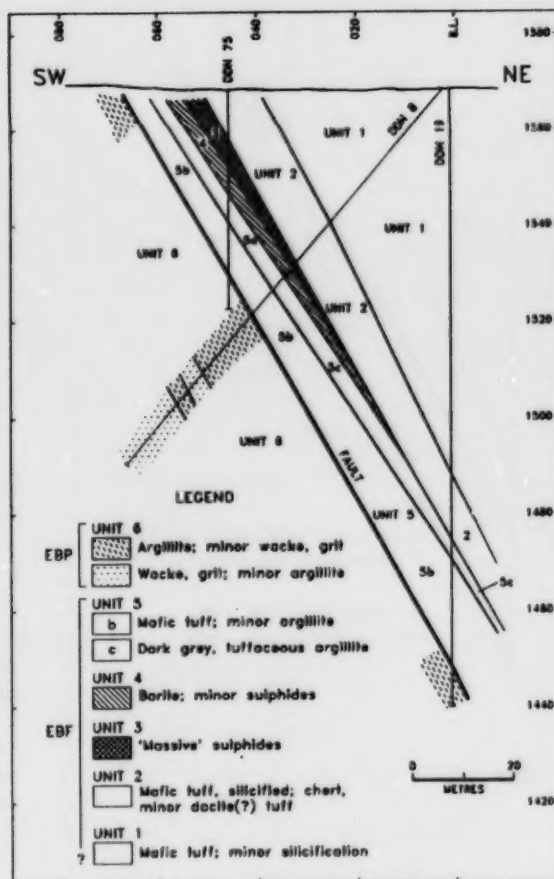


Figure 5-22. Vertical section (97+00) through the R8 sulphide-barite lens, Rea Gold (after Höy and Goutier, 1986).

tonnes of ore. It is currently being re-examined by Kamad Silver Company Ltd. and Minnova Inc.

Homestake is a base and precious metal deposit in intensely altered and sheared sericite schists of Unit EBA of the Eagle Bay assemblage (Schiavizza and Preto, 1987). Mineralization is generally contained in barite lenses that overlie chlorite phyllite and sericite-quartz schist. Ankerite-chlorite phyllite with thin interbeds of argillite and tuffaceous chlorite phyllite overlie the lenses (Höy and Goutier, 1986). The sequence is interpreted to be a succession of andesite tuffs overlain by altered felsic tuffs that contain, near the top, massive barite-sulphide lenses. These are overlain by more andesite tuffs that are intercalated with clastic sedimentary rocks.

Trace element analyses of volcanic rocks of the Homestake succession indicate that they are calcalkaline andesites, dacites and rhyolites (Höy, 1987). These contrast with the alkaline nature of the Eagle Bay rocks that host Rea. However, similarities

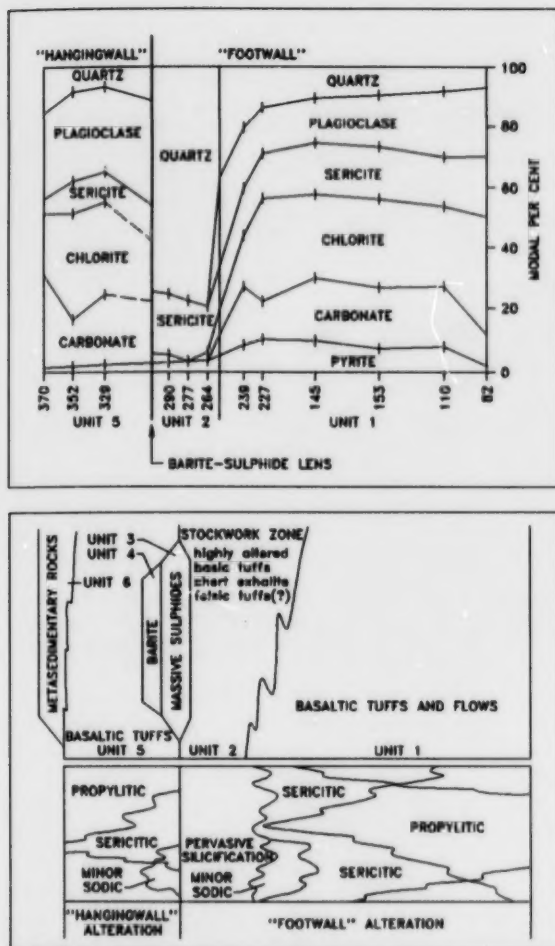


Figure 5-23. (a) Distribution of major minerals involved in alteration of mafic volcanic rocks in both the "hangingwall" (Unit 5) and "footwall" (Units 1 and 2) L97 lens, Rea Gold. The sample numbers refer to feet from surface in Drill Hole 19; note section is inverted (from Höy, 1987). (b) Schematic section through the L97 lens at Drill Hole 19, and alteration zones (from Höy, 1987).

between the deposits include their polymetallic nature, high precious metal content, association with barite, and pronounced footwall alteration zone.

Kutcho Creek (MINFILE 1041 060)

Deposits at Kutcho Creek were discovered in 1973 after exploration of pyritic sericitic schists in the region. Two potentially economic massive sulphide masses and a low-grade deposit now constitute the Kutcho Creek deposit. The following description is summarized from Bridge *et al.* (1986), Panteleyev (1975) and Panteleyev and Pearson (1977).

The Kutcho Creek deposit occurs within the Kutcho Formation, a succession of predominantly

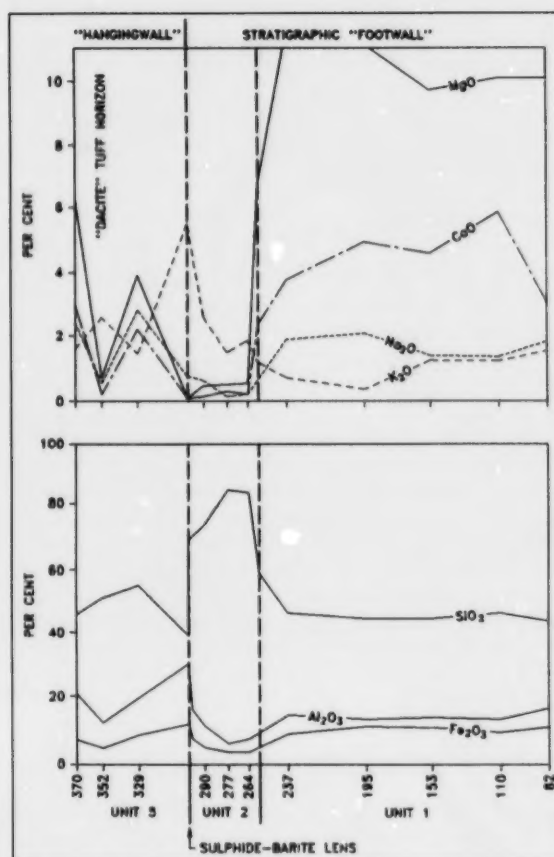


Figure 5-24. Change in major element chemistry of altered mafic volcanic rocks in the stratigraphic footwall and stratigraphic hangingwall of the L97 lens, Rea Gold (from Höy, 1987).

pyroclastic and volcanoclastic rocks of Late Triassic age in the Stikine Terrane. Within the succession are some mafic flows, shales and synvolcanic intrusive rocks. The volcanic succession is bimodal calc-alkaline with basalt to basaltic andesite and rhyodacite to rhyolite predominating.

Massive sulphides occur at a sharp transition between footwall felsic lapilli and minor ash tuff, and hangingwall felsic-crystal and lapilli-crystal tuff. These are overlain sharply by thin-bedded ash, lapilli and crystal tuff, argillite and some mafic rocks (Figure 5-25).

Three deposits, the Kutcho, Sumac West and Esso West deposits, occur along a 3.5-kilometre strike length. However, a zone defined by limonite staining of sericitic schists, quartz-sericitic schists and rare gossans extends for approximately 15 kilometres along the ore horizon (Panteleyev and Pearson, 1977). The deposits are discrete, elongate bodies of massive and disseminated sulphides in quartz-sericitic schist and dolomite-quartz-sericitic rock. The

Kutcho deposit (Figure 5-25, 5-26) has a lower massive pyrite layer that is transitional from disseminated pyrite in the footwall. Base metal concentrations generally occur above this layer in a number of massive sulphide layers interbedded with mineralized dolomite-quartz-sericite rocks. The sulphide minerals include pyrite, sphalerite, chalcopyrite, bornite, minor chalcocite, trace tennantite, galena and digenite; approximately half the copper values are in bornite. Vertical Cu:Zn zonation, common to many massive sulphide deposits, is not recognized in any of the ore lenses.

Alteration envelopes surround the massive sulphide lenses. The most prominent alteration minerals are sericite and dolomite. Sericite is abundant for at least 200 to 300 metres stratigraphically beneath the sulphide deposits and occurs along the ore horizon for at least 4 kilometres. It also occurs in a sharply defined zone of limited extent in the hangingwall of the lenses. Dolomite occurs in dolomite-quartz-sericite lenses in the hangingwall immediately above the sulphide lenses, within the massive sulphide body and disseminated in both the footwall and the hangingwall. Although primary quartz is a common constituent in the volcanic hostrocks, quartz veining and silicification are minor. These alteration envelopes reflect sodium depletion and potassium, calcium and magnesium enrichment, due primarily to the replacement of feldspars by sericite and dolomite.

In summary, the massive sulphide lenses at Kutcho Creek have some similarities with Kuroko-type deposits. In particular, the host succession, dominated by felsic pyroclastic rocks and the pronounced sericitic alteration envelopes are typical of this class of deposit in British Columbia. However, they differ in some aspects – minimal silica alteration, prominent carbonate alteration, lack of sulphate (barite) facies and only minor lead content.

Eskay Creek (MINFILE 104B 008)

Discovery, in September, 1988, of No. 21 zone gold-silver-base metal deposits at Eskay Creek north of Stewart has sparked considerable exploration interest in this part of the province (Britton *et al.*, 1990). The 21A, 21B, 21C and Pumphouse Lake deposits are stratabound massive sulphide lenses within the Early to Middle Jurassic Hazelton Group. Geological reserves (excluding 21A), with a gold cut-off grade of 3.4 grams per tonne, total 3 968 000 tonnes containing 26 grams per tonne gold and 998 grams per tonne silver (Table 5-3).

The Hazelton Group comprises a thick and heterogeneous succession of dominantly andesite, dacite and rhyolite with intercalated sediments. It overlies the Late Triassic Stuhini Group and is overlain by the Middle to Late Jurassic Bowser Lake Group. Within the Eskay Creek area, the Hazelton Group has been subdivided into four formations: the Unuk

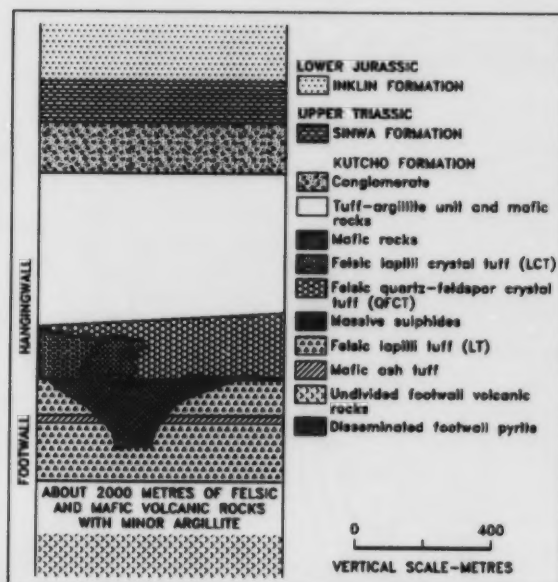


Figure 5-25. Stratigraphic column for the Kutcho Creek deposit area with an idealized north-south section across the Kutcho massive sulphide deposit (from Bridge *et al.*, 1986).

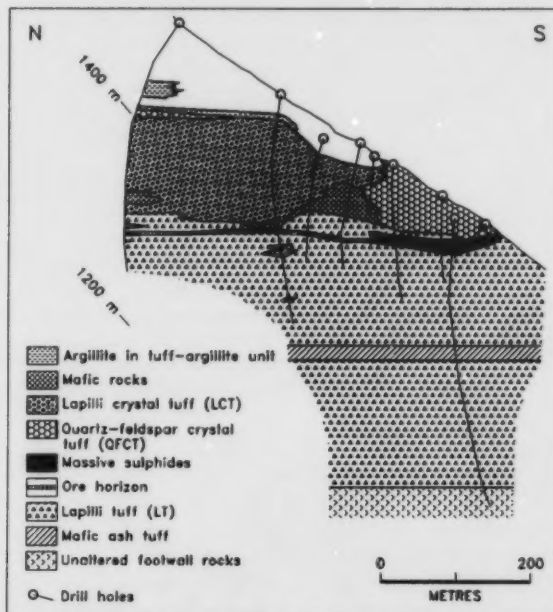


Figure 5-26. Geologic section through the east end of the Kutcho deposit (from Bridge *et al.*, 1986).

River, Betty Creek, Mount Dilworth and Salmon River formations (Alldrick *et al.*, 1989; Britton *et al.*, 1990).

The Unuk River Formation is a thick sequence of fine grained andesite pyroclastics and flows with tuffaceous turbidite, wacke and conglomerate interbeds. It is overlain by the Betty Creek Formation

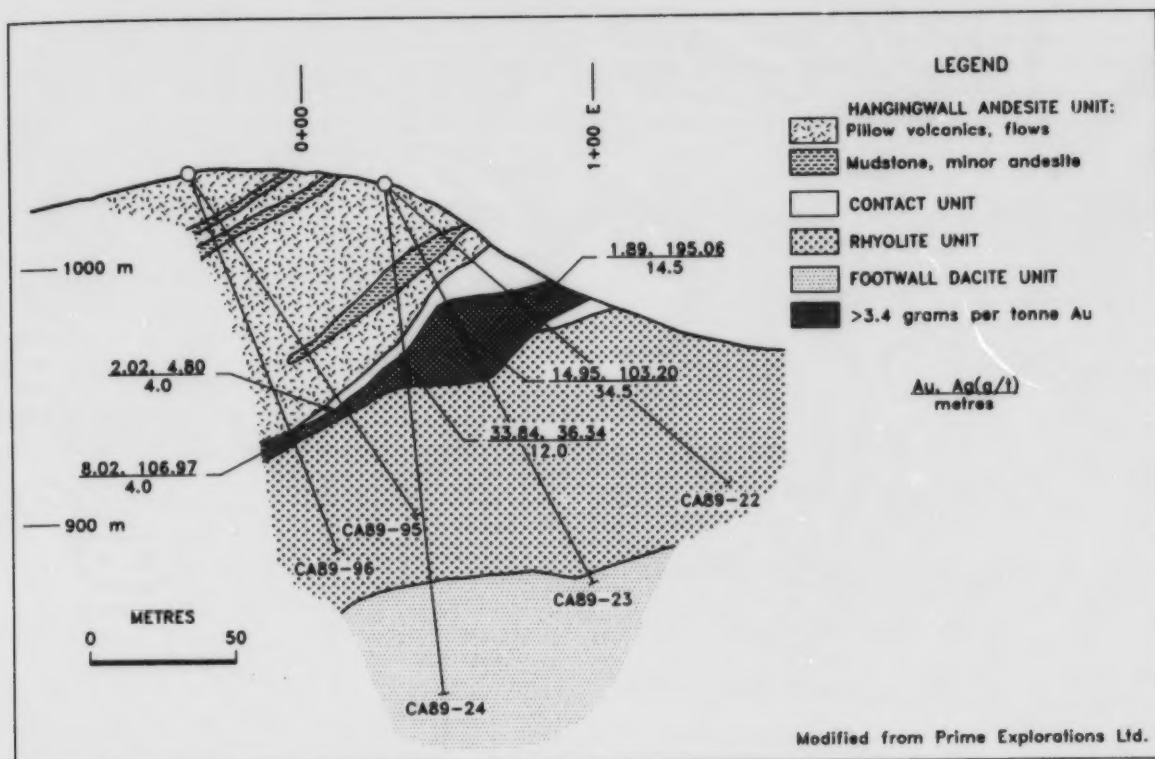


Figure 5-27. Section 0+00, 21A deposit, Eskay Creek (from Britton et al., 1990).

which comprises andesite to dacite tuffs and flows interbedded with epiclastic deposits. Purple tuff units and airfall pyroclastic deposits indicate local sub-aerial exposure. The Mount Dilworth Formation, a thin sequence of dominantly felsic pyroclastic rocks or silicified bedded rocks (A. Ettlinger, personal communication, 1991) overlies the Betty Creek Formation. The uppermost formation of the Hazelton Group, the Salmon River Formation, is subdivided in the Eskay Creek area into a lower member (the contact unit) that consists of carbonaceous mudstone with minor rhyolite-mudstone breccia overlain by and an upper member (the hangingwall andesite) of pillowed flows and breccias and mudstone. The contact unit rests unconformably on the Mount Dilworth Formation and hosts the main sulphide layers.

A variety of deposit types have been recognized in the Eskay Creek area. The following description of these deposits is summarized from Britton et al. (1990), Idziszek et al. (1990) and Blackwell (1990). They include stratabound gold and silver mineralization associated with antimony, arsenic and mercury (21A deposit), stratabound sphalerite-rich massive sulphide layers with high gold and silver values (southern 21B deposit) and stratabound base metal rich lenses, also with high gold and silver values (northern 21B deposit). Crosscutting fissure veins and disseminations carrying gold, silver, lead, zinc

and minor antimony and arsenic occur in the Mount Dilworth rhyolite and the Betty Creek andesite.

The massive sulphide lenses are the focus of this overview paper and are hence described in more detail. Exploration has identified at least two other stratabound deposits, the 21C and the Pump-house Lake zone, but these are less well documented than the 21A and 21B deposits.

The 21A deposit consists of disseminated to near massive stibnite and realgar within the contact unit, underlain by stockwork-style disseminated sphalerite, tetrahedrite and pyrite in quartz-chlorite-muscovite breccias in the adjacent footwall rhyolite (Blackwell, 1990). The mineralized zone is approximately 280 metres long, up to 100 metres wide, and averages 10 metres in thickness (Figure 5-27). Geological reserves total 968 000 tonnes containing 9.6 grams per tonne gold and 127 grams per tonne silver.

The 21B deposit is separated from the 21A deposit by 140 metres of weakly mineralized mudstone and rhyolite. The southern 600 metres of the 21B deposit is a stratiform sheet of banded high-grade gold and silver-bearing base metal sulphides within the contact unit. It varies in thickness from 2 to 12 metres. Sulphide minerals include sphalerite, tetrahedrite, boulangerite and bournotite with minor galena in a

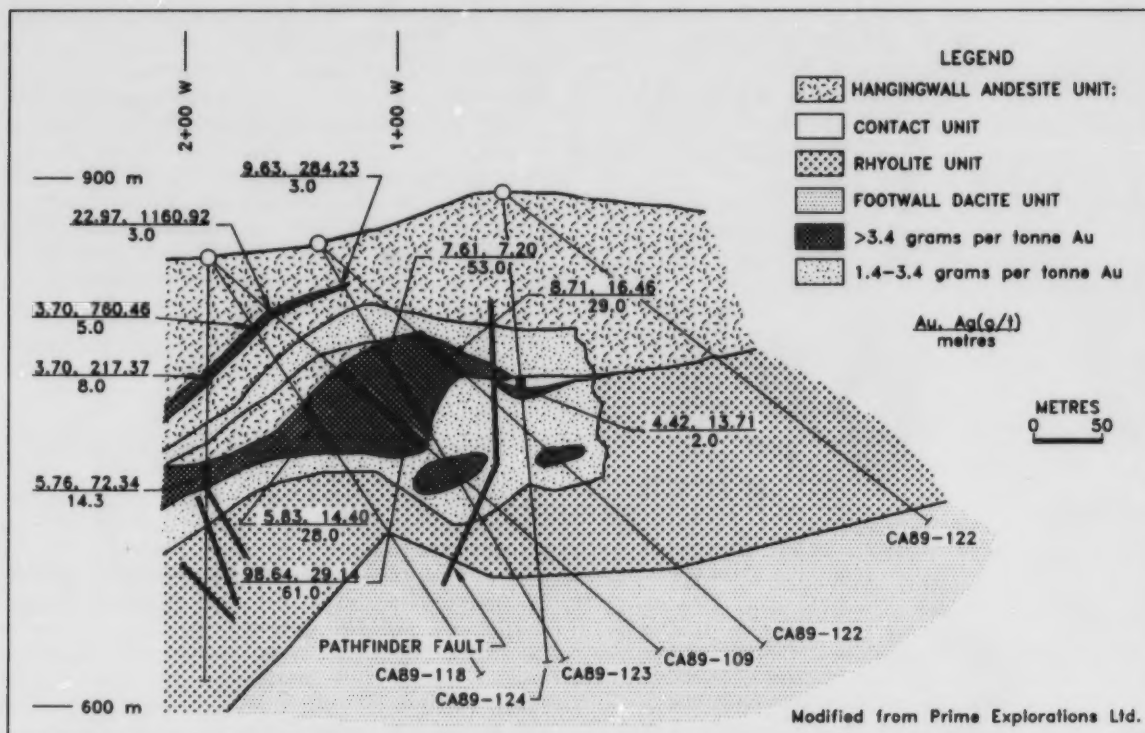


Figure 5-28. Section 9+00N, 21B deposit, Eskay Creek (from Britton *et al.*, 1990).

gangue of magnesium chlorite, muscovite, potassium feldspar and calcite. Graded and laminated sulphide beds with slump structures and basal scours indicate that the sulphides have been transported. Although footwall alteration is rare in the southern 21B deposit, areas of micro-fracture veinlets that carry tetrahedrite, pyrite and minor boulangerite occur locally.

The northern 300 metres of the 21B deposit is more complex. Base metal-rich lenses with gold and silver occur in mudstones at several stratigraphic levels: within the hangingwall andesite, the contact unit and the underlying rhyolite unit breccias (Figure 5-28). The sulphide lenses in the hangingwall andesite comprise massive dark sphalerite, galena, tetrahedrite and barite with minor pyrite and chalcopryrite. The lenses in the contact unit comprise sphalerite, tetrahedrite and boulangerite(?) with galena and chalcopryrite.

High grade mineralization in the 21B zone also occurs as crosscutting zones in the contact unit and deeper in the rhyolite unit (Britton *et al.*, 1990). These include quartz-carbonate veins and breccias with numerous sulphide veinlets and disseminations of sphalerite and pyrite, with minor galena, chalcopryrite, tetrahedrite and visible gold.

In summary, the 21A and 21B deposits are essentially high-grade polymetallic sulphide lenses in

mudstones at or near the transition between siliceous volcanic rocks of the Mount Dilworth Formation and andesites of the Salmon River Formation. Stockwork-style base and precious metal mineralization associated with silicification and quartz-chlorite-sericite alteration occurs beneath and adjacent to some of the sulphide lenses. The stratabound nature of the lenses, evidence of synsedimentary formation, occurrence in bimodal, calcalkaline arc volcanics and association with silicified stockwork zones suggests that they are VMS deposits. However, the mineralogy and precious metal enrichment are unusual (Britton *et al.*, 1990). It is possible that a shallow marine environment, in contrast with the typical deep-water environment recognized in virtually all VMS deposit sites, may account for their unusual chemistry. Alternatively, No. 21 zone mineralization may represent, at least in part, a low temperature epithermal system.

SUMMARY — VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS IN B.C.

Volcanogenic massive sulphide deposits in British Columbia are generally either copper-zinc rich or zinc-lead-copper rich. Copper-zinc deposits are subdivided into two main types; those dominantly in mafic volcanic rocks and interpreted to have formed at or near a divergent plate boundary are similar to

the ophiolite-hosted Cyprus-type deposits, whereas those in a mixed mafic volcanic-terrigenous sedimentary succession formed near continental masses, possibly in back-arc basins or during early stages of continental separation. These deposits are similar to Besshi-type deposits. Zinc-lead-copper deposits are similar to Kuroko-type deposits and are interpreted to have formed in a rift during constructive arc development. These various tectonic settings are reflected in the chemistry of host volcanic rocks. Cyprus-type deposits are in tholeiitic or calcalkaline basalts, Besshi deposits are usually associated with mafic calcalkaline basalts, whereas Kuroko-type bodies are in pyroclastic felsic rocks in bimodal, calcalkaline suites or less commonly alkaline volcanic rocks.

Although VMS deposits in British Columbia range in age from Early Paleozoic to Late Mesozoic or possibly Early Tertiary, most occur in either the Early Paleozoic, Late Devonian or Late Triassic. Lower Paleozoic deposits are in the pericratonic Kootenay Terrane in southeastern British Columbia; they formed during a period of regional subsidence related to extensional tectonics along the western margin of cratonic North America. Late Devonian deposits of the Eagle Bay assemblage of the Kootenay Terrane formed during a period of arc volcanism; this time corresponds approximately with compressive tectonics of the Cariboo and Antler orogenies. Arc volcanism occurred in Late Triassic and early Jurassic time throughout the accreted terranes.

Exploration for VMS deposits in the Canadian Cordillera should first be directed towards volcanic or volcanic-sedimentary packages that formed in marine environments. Virtually all host successions formed in "deep-water" marine environments. Environments with considerable proportion of epiclastic rocks and maroon volcanic rocks, indicative of periodic emergence, are not favourable sites for VMS deposition. These include much of the Late Triassic Nicola Group and the dominantly Jurassic Hazelton Group. However, the Eskay Creek deposits, interpreted to have formed in shallow marine volcanics of the Hazelton Group, are unusual but rich exceptions to these generalities.

Volcanogenic massive sulphide deposits are also uncommon in some Early Jurassic volcanic successions, such as the Rossland Group in southeastern British Columbia, despite these rocks being an inferred arc setting. The lack of massive sulphide deposits is interpreted to be related to the lack of differentiated bimodal volcanics in these arcs and the prominent basalt-andesite and minor rhyodacite assemblages.

Further exploration in suitable terranes and host successions should initially be directed at locating favourable horizons — the occurrence of felsic volcanics or breaks in volcanic activity marked by silica exhalites or pelagic sedimentation. The recognition

of early structures is important as these commonly localize hydrothermal discharge areas. Detailed exploration should focus on recognition of alteration zones, either the large "semiconformable" zones or more proximal silica, chlorite or sericite zones.

ACKNOWLEDGMENTS

I would like to acknowledge many discussions with staff of the Geological Survey Branch regarding the geology of various British Columbia massive sulphide deposits and their tectonic setting. I would also like to thank geologists in the exploration and mining community in British Columbia. They are always helpful in providing data and information; their cooperation is much appreciated.

Kathryn Dunne (Andrew) is thanked for her continued help and support. Much of the deposit research and data compilation is due to her efforts.

The editorial comments of John Newell and Brian Grant of the Geological Survey Branch and Bob Turner of the Geological Survey of Canada, and discussions with R. Zierenberg of the U.S. Geological Survey, are much appreciated.

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METALLOGENY OF ULTRAMAFIC-MAFIC ROCKS IN BRITISH COLUMBIA WITH EMPHASIS ON THE PLATINUM-GROUP ELEMENTS

by Graham T. Nixon and Janet L. Hammack

INTRODUCTION

This paper presents a synopsis of mineral deposits that are hosted by, or spatially associated with, ultramafic-mafic complexes in the Cordillera. For present purposes, we have focused on the base and precious metal commodities, notably chromite, nickel, platinum-group elements (PGE) and gold, with a bias towards the platinum-group elements. Deposits in ultra-alkaline complexes such as kimberlites, carbonatites and lamproites are excluded. We start by examining the geological environment of each commodity in turn, using descriptive models for relevant deposit types, and then proceed to discuss examples. In this way, we hope to provide a basic understanding of the nature and distribution of ultramafic-mafic-associated mineral occurrences in relation to their tectonic setting. This synopsis should serve the needs of the mineral explorationist and may even delineate areas worthy of future endeavours.

The compilation and descriptions of mineral occurrences that follow are derived from the MINFILE database (Jones, 1989) and are therefore confined to British Columbia. For brevity, we have treated only the more significant occurrences. The dataset abstracts from previously published and unpublished information, the sources of which are referenced in the text. In the descriptions that follow, it is assumed that the reader is already familiar with certain aspects of the geography and geology of British Columbia.

TERMS AND DEFINITIONS

TECTONIC SETTING

The nomenclature of tectonic elements is based on the Tectonic Assemblage Map of the Canadian Cordillera (Wheeler and McFeely, 1987). Late Paleozoic–Early Mesozoic oceanic and volcanic-arc terranes were accreted to the miogeoclinal margin of cratonic North America in the Middle to Late Mesozoic. The accreted terranes form two superterrane: the Intermontane Superterrane (predominantly Quesnellia, Stikinia, Cache Creek, and Slide Mountain terranes), which had amalgamated by the Late Triassic and was accreted to ancestral North America in Jurassic time; and the Insular Superterrane (mainly Wrangell and Alexander terranes), which

amalgamated by the Late Jurassic to Early Cretaceous and was accreted to the growing continental margin before the end of the Cretaceous. A host of smaller accreted terranes of the Coast Belt lie between these two superterrane.

Of prime importance for the distribution of ultramafic-mafic rocks and their associated mineral deposits are the oceanic or marginal-basin lithologies of the Cache Creek, Slide Mountain and Bridge River (Coast Belt) terranes, and arc-related volcanic and plutonic assemblages of Quesnellia and Stikinia. The oceanic terranes contain serpentinites and Alpine peridotites, many of which represent tectonically disrupted ophiolite packages and accretionary prisms, and include mélanges and blueschists. Ultramafic-mafic intrusive complexes are represented by Alaskan-type bodies that are generally considered to be coeval with mafic to intermediate, pre-accretionary arc volcanism.

Nomenclature of Ultramafic-mafic Rocks

The classification of ultramafic rocks used in this paper is shown in Figure 6-1. This scheme is essentially the IUGS classification (Le Maitre, 1989) with the exception that the field of wehrlite has been arbitrarily subdivided into olivine wehrlite and wehrlite, which constitute major mappable units in many of the Alaskan-type complexes of British Columbia. Other rock types of importance are

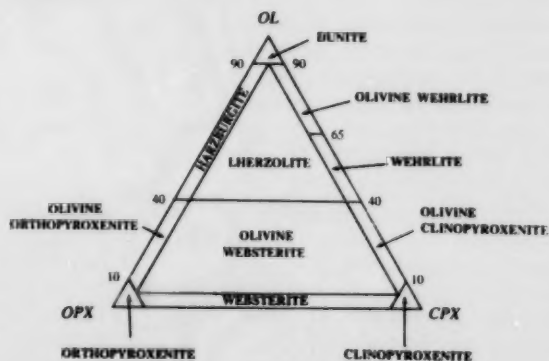


Figure 6-1. Classification of the ultramafic rocks (modified after Le Maitre, 1989).

hornblende-bearing ultramafics that include hornblende clinopyroxenite (10–50 per cent hornblende; 90–50 per cent clinopyroxene), clinopyroxene hornblendite (10–50 per cent clinopyroxene; 90–50 per cent hornblende) and hornblendite (<10 per cent clinopyroxene). The common gabbroic rocks include gabbro *sensu stricto* (essential clinopyroxene+calcic plagioclase >An₅₀), and hornblende gabbro or diorite (sodic plagioclase <An₅₀). The transition from ultramafic to gabbroic or dioritic rocks is marked by a gradual increase in plagioclase which changes from intercumulus to cumulus in nature.

ALASKAN-TYPE COMPLEXES

The Alaskan-type complexes are named for a distinctive suite of ultramafic-mafic intrusions distributed along a narrow, northerly trending, 600 kilometre-long belt in southeastern Alaska. Commonly used synonyms include Alaskan-Ural, Uralian, concentric or zoned ultramafic complexes. The geological and petrographic features of Alaskan-type complexes have been summarized by Taylor (1967). The Duke Island ultramafic intrusion is best-documented (Irvine, 1974a), although its spectacularly developed layering is atypical of Alaskan-type complexes in general. Most of these complexes have been interpreted to represent crystal cumulates of mantle-derived ultramafic magmas. The early work on Alaskan-type intrusions described these crudely stratiform cumulate sequences as remobilized and diapirically re-emplaced high in the crust. However, the internal textures and contact relationships of many Alaskan-type bodies in British Columbia do not support this diapiric re-emplacement model, and leave little doubt that these cumulates were deposited more or less *in situ* in crustal magma chambers.

Ultramafic lithologies characteristic of Alaskan-type complexes lie along the olivine-clinopyroxene join in Figure 6-1. Early cumulate minerals are typically represented by forsteritic olivine, chromite, diopsidic clinopyroxene, and rare phlogopitic mica, whereas hornblende, biotite, magnetite and plagioclase (plus minor apatite and ilmenite) predominate in the more evolved rocks. The lack of orthopyroxene-bearing cumulates in Alaskan-type complexes has been taken to indicate a mildly alkalic rock series (Irvine, 1974a) and serves to distinguish them from ophiolite assemblages.

One of the key attributes of Alaskan-type complexes is a crude zonation of rock types ranging from dunite through wehrlite and clinopyroxenite to hornblende clinopyroxenite and hornblendite (locally feldspathic). In some cases, a crudely concentric zonation of rock types is apparent, ranging from dunite in the core to hornblende-bearing lithologies at the margins of the complex. In British Columbia, these ultramafic lithologies are com-

monly enveloped by gabbroic to dioritic rocks that may be comagmatic, and some intrusions have well-developed contact aureoles that reach lowermost amphibolite grade.

OPHIOLITES

Ophiolite complexes are widely perceived to represent the remnants of oceanic or marginal basin lithosphere that were obducted during arc-continent or continent-continent collisions (Coleman, 1977). They comprise a distinctive stratigraphy of rock types that typically include (from top to bottom) pillow basalts with thin interbedded pelagic sediments, sheeted dikes, uniform gabbros, mafic to ultramafic cumulates, and tectonized mantle peridotites. The latter group of rocks comprise harzburgites and lherzolites, and differ mineralogically from Alaskan-type ultramafic rocks in the presence of orthopyroxene (Figure 6-1). Ophiolite stratigraphy is rarely preserved intact and is commonly tectonically disrupted during emplacement. The ophiolite suite is notable for its economically important deposits of chromite, and it is spatially associated with lode gold occurrences as discussed below. One of the best documented examples in British Columbia is the Shulaps ophiolite (Calon *et al.*, 1990).

MINERAL DEPOSIT TYPES

The mineral deposit types of most significance in this review are listed in Table 6-1 along with some of their characteristic attributes. They represent ultramafic-mafic-hosted chromite and nickel-copper sulphides, and lode and associated placer occurrences of PGE and gold. With few exceptions, the deposit types listed refer to specific descriptive models compiled by Cox and Singer (1986). The model for listwanite-associated lode gold is taken from Buisson and Leblanc (1986), although Cox and Singer (1986) included many key aspects of this deposit type in their descriptions of low-sulphide gold-quartz veins (Model 36a). In addition, a new subclass of Alaskan-type PGE mineralization (Model 9, subtype 3 in Table 6-1) has recently been recognized by Johan *et al.* (1989). Significant nonmetallic deposits not described here include serpentine-hosted asbestos as developed at the world-class Cassiar mine, for example (Model 8d; and Eckstrand, 1984, deposit type 26), and nephrite-jade deposits which also occur in the Cassiar area.

Most of the mineral deposit descriptors (or synonyms) in Table 6-1 will be familiar, with the possible exception of listwanite, a term used to describe a serpentinized ultramafic rock that has been hydrothermally altered to an assemblage of predominantly carbonate and quartz, and which may host native gold. The principal features of each deposit type are summarized below and applied to analogous deposits in British Columbia.

TABLE 6-1

Some Significant Ultramafic-Mafic-Associated Deposit Types in the Cordillera

Model/(Ref.) ¹	Descriptor ¹	Commodities ²	Ore Mineralogy	Examples ³
LODE:				
7a	Synorogenic-synvolcanic Ni-Cu (gabbroid-associated)	Ni, Cu (Co, PGE, Au, Ag)	Pyrrhotite, pentlandite, chalcopyrite, pyrite, Ti-magnetite, Cr-magnetite (graphite)	Giant Mascot, B.C. <i>Rana, Norway</i> <i>Moxie, USA</i>
8a,b	Podiform chromite (Alpine-type)	Cr, Fe (PGE)	Chromite, ferritchromite, magnetite (PGE alloys, laurite)	Scottie Creek, B.C. <i>Coto Mine, Philippines</i> <i>Tiebaghi, New Caledonia</i>
9	Alaskan-type PGE (zoned ultramafic Cr-Pt)	PGE (Cr, Fe, V, Ti, Cu, Ni)	1. Chromite, PGE alloys (pentlandite, pyrrhotite, gold) 2. Ti-V magnetite (PGE alloys, cooperite, bornite, chalcopyrite) *3. PGE alloys, cooperite	Tulameen, B.C. <i>Urals, USSR</i> Tulameen, B.C. <i>Lower Coon Mountain, USA</i> <i>Fifield, NSW, Australia</i>
(1)	Listwanite Au	Au, Ag, PGE	Native gold, (base metal sulphides, arsenides)	Atlin, B.C. <i>Bou Azzer, Morocco</i> <i>Mother Lode, California(?)</i>
PLACERS:				
39a	Placer Au-PGE	Au (PGE)	Native gold, PGE alloys, (Au commonly attached to quartz and magnetite)	Atlin, B.C. <i>Sierra Nevada, California</i>
39b	Placer PGE-Au	PGE (Au)	PGE alloys (native gold, magnetite, chromite, ilmenite)	Tulameen, B.C. <i>Goodnews Bay, Alaska</i> <i>Urals, USSR</i> <i>Choco, Columbia</i>

¹ Model numbers and descriptors refer to deposit types of Cox and Singer (1986); except Ref. (1): listwanite model of Buisson and Leblanc (1986); in part equivalent to model 36a of Cox and Singer (*ibid.*).

² PGE, Platinum-group Elements.

³ Well-known examples outside B.C. are italicized.

* A third subtype not previously recognized (Johan *et al.*, 1989).

CHROMITE

Chromite, the major economic source of chromium, is a member of the spinel mineral group with the formula $\text{Fe}^{+2}\text{Cr}_2\text{O}_4$, or more generally $\text{R}^{+2}(\text{R}^{+3})_2\text{O}_4$ where Mg, Ni and Zn substitute for R^{+2} , and Fe^{+3} , Al and Ti for R^{+3} . The Cr_2O_3 content and Cr/Fe ratio of the chromite determine its market category: metallurgical ($\text{Cr}_2\text{O}_3=40-55$ weight per cent; Cr/Fe 1.8-4.0) for the production of ferro-chromium used in special steels; chemical (>42 weight per cent Cr_2O_3 ; Cr/Fe as low as 2.0) for pigments and dyes; and refractory ore ($\text{Cr}_2\text{O}_3+\text{Al}_2\text{O}_3>60$ weight per cent) for foundry sands and briquettes. Chromium is classed as a strategic metal since it is indispensable for many industrial purposes. Canada currently has no domestic production and supply is dominated by few countries (Tables 6-2 and 6-3).

CHROMITE DEPOSIT MODEL

Economic concentrations of chromite, the ore rock chromitite, occur in two principal geologic

environments: large ultramafic-mafic stratiform intrusions (e.g., Bushveld, South Africa) and Alpine-type peridotites. Excellent summaries of these environments and ores are given by Duke (1983) and Stowe (1987). The stratiform chromitites account for over 90 per cent of world chromite reserves. However, Alpine-type or podiform chromitites currently comprise more than half of world production and have accounted for some 57 per cent of all chromite produced. These ores are the sole source of high-grade metallurgical chrome and it would clearly be a mistake to ignore their importance from an exploration point of view.

Phanerozoic podiform chromitites are the most viable exploration target in the Cordillera (Figure 6-2). They are hosted by the so-called Alpine-type ultramafic complexes of orogenic belts, the majority of which represent tectonically emplaced ophiolite slivers. The term "Alpine-type" is usefully retained for intensely deformed and serpentinized ultramafic bodies of questionable origin, or peridotites of other affinity (e.g., subcontinental mantle fragments).

TABLE 6-2

World Average Annual Chromite Production Per Decade ($\times 1000$ Tons)

	1900- 1909	1910- 1919	1920- 1929	1930- 1939	1940- 1949	1950- 1959	1960- 1969	1970- 1979	1984*
South Africa....	—	—	15	92	240	613	973	2207	3394
USSR.....	21	4	18	148	358	647	1343	2022	3300
Albania.....	—	—	—	6	119	315	735	1500	—
Zimbabwe.....	6	54	138	130	395	420	439	574	500
Turkey.....	11	8	10	122	199	672	445	525	500
Philippines.....	—	—	—	28	144	519	528	504	300
India.....	4	15	41	38	39	57	100	334	—
Finland.....	—	—	—	—	—	—	11	256	—
Iran.....	—	—	—	—	—	27	105	177	—
Brazil.....	—	2	1	1	3	4	15	159	1000
Malagasy.....	—	—	—	—	—	—	13	155	—
Greece.....	9	7	15	31	12	41	38	28	—
Sudan.....	—	—	—	—	—	—	16	25	—
Cyprus.....	—	—	1	2	5	10	13	25	—
Japan.....	—	4	6	27	38	41	46	22	—
Cuba.....	—	2	21	44	177	71	15	21	—
Pakistan.....	—	—	—	—	6	21	21	15	—
Yugoslavia.....	—	—	10	51	51	116	75	12	—
New Caledonia.....	32	51	40	57	57	74	9	4	—
United States..	—	19	—	1	33	94	17	—	—
Sierra Leone....	—	—	—	1	13	18	2	—	—
Canada.....	5	10	2	1	8	—	—	—	—
Other.....	1	3	—	1	1	3	—	9	706
Totals.....	89	179	318	775	1785	3567	4539	7809	11200

Sources: Calculated from Duke, 1982; De Young *et al.*, 1984; and Eadie, 1984 with additions.

* Best available estimates for the year 1984 (from Stowe, 1987a).

TABLE 6-3

World Chromite Mine Production (1987-1988)
And Chrome Ore Reserves

Country	Mine Production		Chrome Ore Reserves
	1987	1988*	1988
(Thousand tonnes, gross weight)			
Republic of South Africa.....	4 175	4 375	913 000
U.S.S.R.....	3 470	3 470	142 000
Albania.....	915	915	7 000
Finland.....	785	785	19 000
Turkey.....	660	667	5 000
Zimbabwe.....	595	650	19 000
India.....	575	675	15 000
Brazil.....	250	300	9 000
Philippines.....	190	220	15 000
Cuba.....	135	150	—
Madagascar.....	110	110	—
Greece.....	70	70	—
New Caledonia.....	68	68	—
Other market economy countries.....	100	24	17 000

Sources: U.S. Bureau of Mines, Mineral Commodity Summaries 1988;
Energy, Mines and Resources Canada.

* Estimated;

—Not available.

Data taken from Canadian Minerals Yearbook 1988 (1989a).

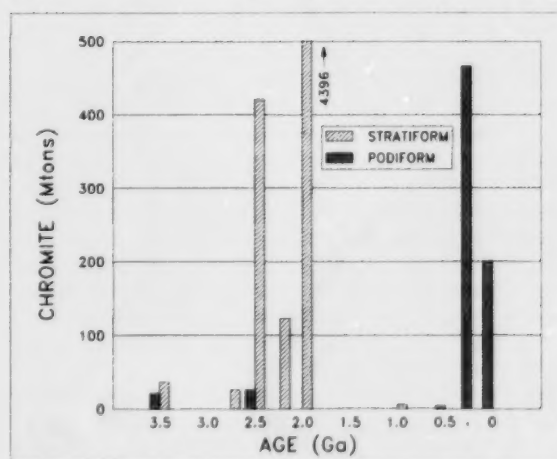


Figure 6-2. Age distributions of Bushveld-type (stratiform) and Alpine-type (podiform) chromite ore fields. Age class interval is 0.25 Ga. Estimates of total chromite ore (million metric tons) include past production and reliable estimates of economic and marginal grade resources (after Stowe, 1987c).

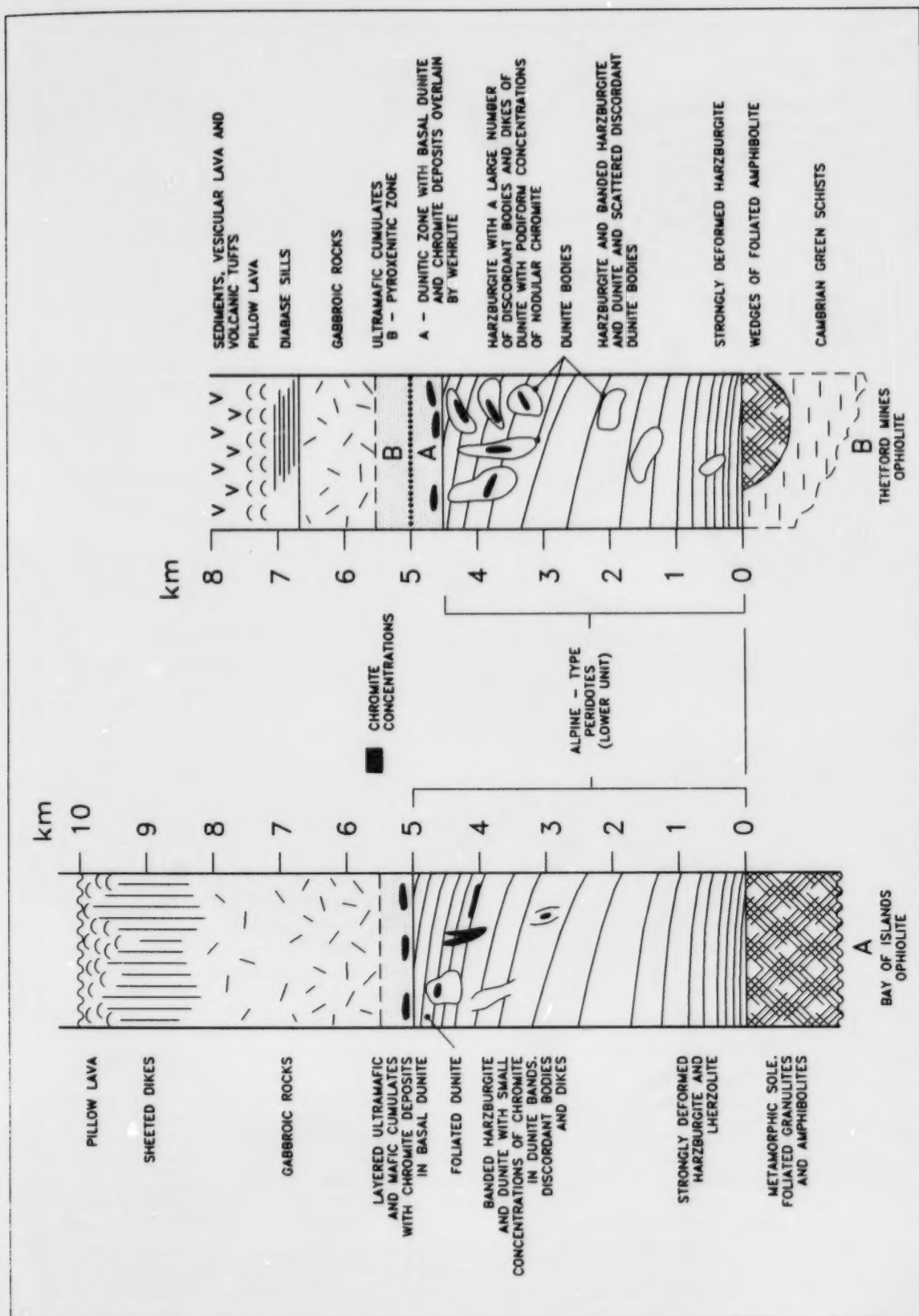


Figure 6-3. Sequence of rock types and position of chromite deposits in the Bay of Islands and Thetford Mines ophiolites (after Laurent and Kacira, 1987).

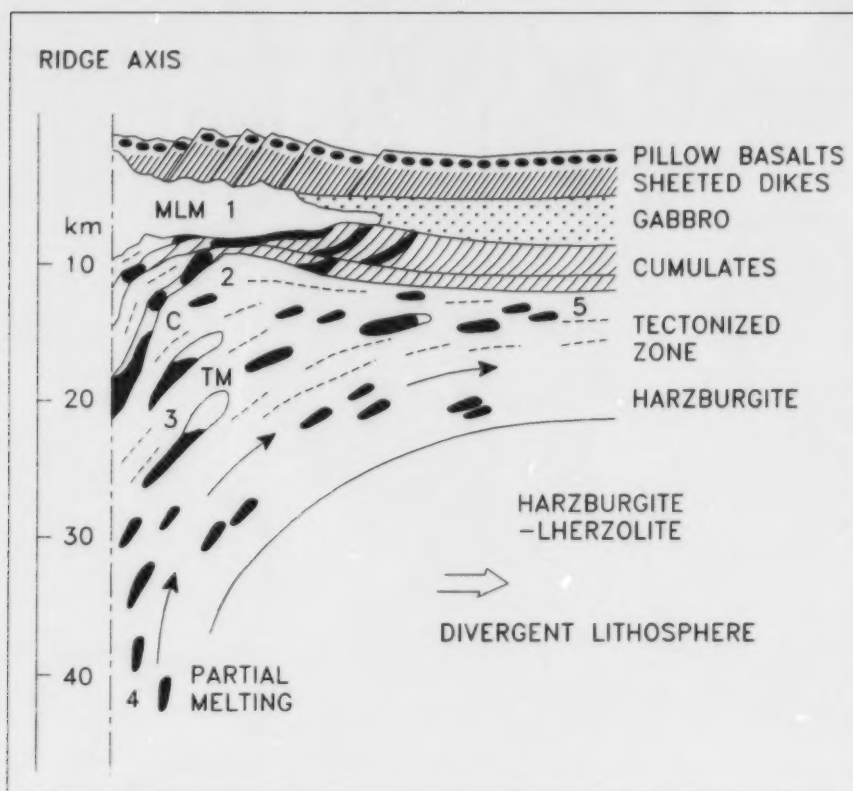


Figure 6-4. Schematic sections across a mid-ocean ridge, showing sites of potential chromite deposition. 1, floor depressions in the main cumulate magma chamber (MLM); 2, pipe-like aggregates in underlying magma conduits (C); 3, early chromite-olivine fractionates in small transient magma chambers (TM) in the rising mantle harzburgite; 4, pods of partial melting residue, previously formed at deeper levels; 5, podiform orebodies are sheared into concordance in the tectonite zone (after Stowe, 1987b).

Geologic sections through two well-studied Canadian ophiolites are shown in Figure 6-3 and are considered to represent sections through obducted ocean lithosphere. Pod-like masses of chromitite are found in variably deformed dunite bodies within tectonized peridotite and olivine-rich crystal cumulates near the mantle-ultramafic cumulate rock transition zone. Chromite ores within the tectonized peridotite are commonly deformed and exhibit nodular, pull-apart and gneissic textures indicative of high-temperature ductile deformation. Large tonnage mining operations generally rely upon favourable spatial distributions of multiple podiform orebodies.

The structural and stratigraphic characteristics of podiform chromitites are forged by processes at spreading centres in oceanic or back-arc basins (Figure 6-4). Chromite concentrations may be generated as partial melting residues or accumulations of crystals in relatively shallow magma chambers that migrate away from the ridge crest during the generation of ocean lithosphere. Many factors combine to determine the specific location and extent of deformation of chromite orebodies, some of which are illustrated in Figure 6-4. The majority of podiform chromitites occur within dunite pods in the uppermost part of the tectonized zone. Some chromitites are sheared into concordance with tec-

tonite fabrics in their journey from the ridge crest; others are discordant and in part may represent the fractionation products of off-axis magma chambers. Ultimately, the podiform environment may be exposed in orogenic belts after obduction and tectonic dismemberment of the ophiolite package.

CHROMITE OCCURRENCES

Chromite occurrences in British Columbia are restricted to two principal environments: podiform chromites as described above, and chromitites found in Alaskan-type complexes. Chromitites in the Alaskan-type environment are not a significant resource of chromium, but are considered later in relation to their platinum-group element potential. The remaining occurrences are related to alpine-type peridotites or serpentinites, many of which are ophiolitic slivers. Most chromite occurrences in British Columbia appear to fit into the small tonnage category (model 8a) of Cox and Singer (1986). These deposits formed prior to amalgamation of the Intermontane Superterrane and were obducted in the Mesozoic during closure of oceanic or marginal basins.

Limited mining of chromite in British Columbia occurred principally in the period 1930 to 1940 but

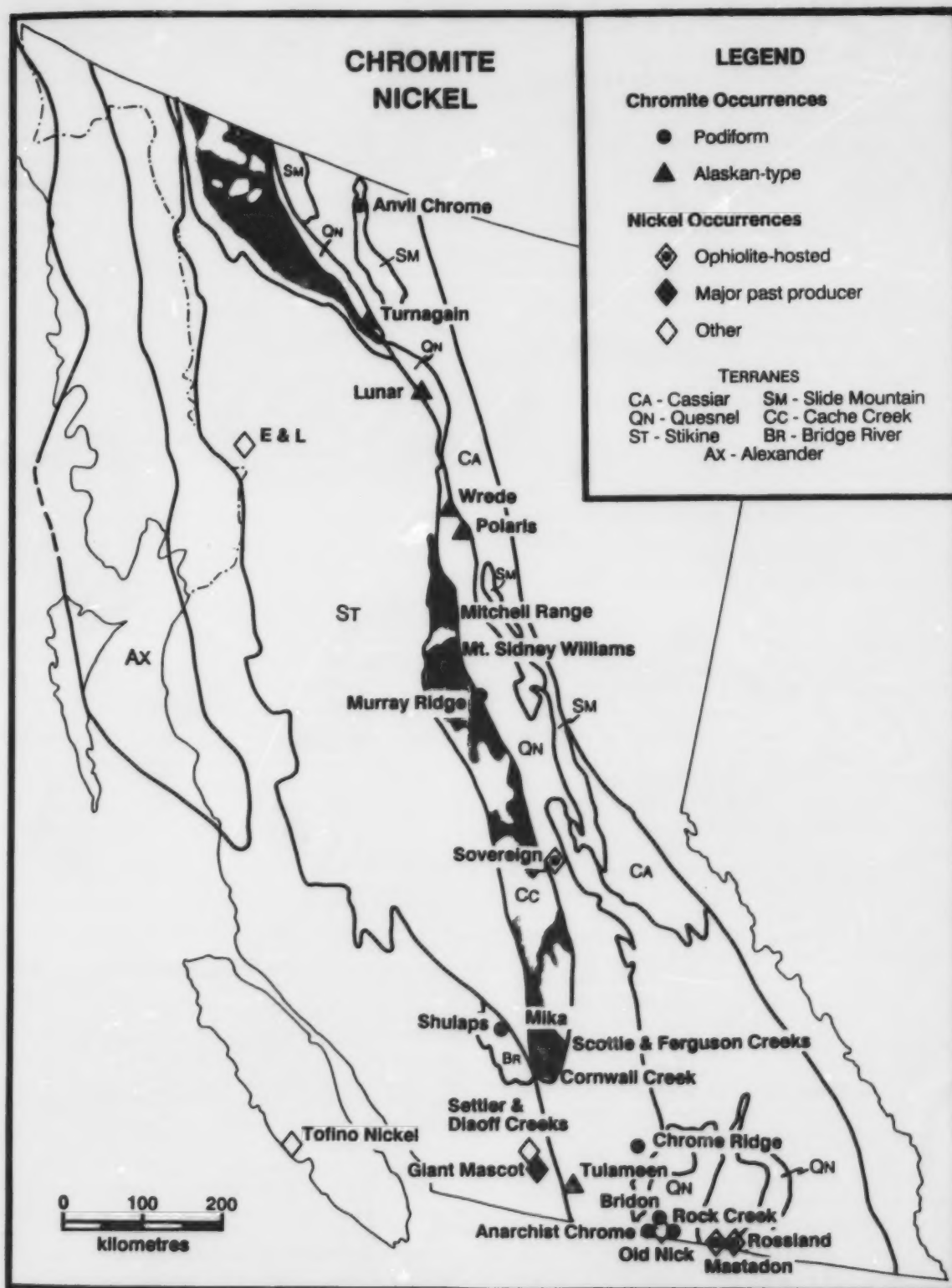


Figure 6-5. Chromite and nickel occurrences in British Columbia in relation to major tectonostratigraphic terranes and oceanic assemblages (shaded).

production was minor and sporadic. The more significant chromite occurrences are shown in Figure 6-5 in relation to their tectonic setting.

The Cache Creek Terrane boasts the largest number of showings. Chromite occurrences in central British Columbia at Murray Ridge, Mount Sidney Williams, and the Mitchell Ranges are part of a northwest-trending disrupted ophiolite package at the eastern margin of the Cache Creek Terrane near the Pinchi Fault (Hancock, 1990a). Rock types include variably serpentinized and tectonized harzburgite, pyroxenite, gabbro and dunite. Chromite locally forms heavy disseminations (<2 m thick), thin layers, nodules and massive pods (<1.5 m wide×12 m long) hosted by serpentinized dunite and harzburgite tectonite (Figure 6-6). Assays of grab samples have yielded 39 to 46 weight per cent Cr_2O_3 , Cr/Fe ratios of 2 to 4, and generally low platinum-group element abundances (<100 ppb).

The Mika and Scottie, Ferguson and Cornwall Creek occurrences lie within a Late Triassic subduction complex at the southern end of exposure of the Cache Creek Group. All are hosted by serpentinite or serpentinized dunite and harzburgite (Hancock, 1990a). Dunite layers within the harzburgite locally reach 60 metres in width. Chromite occurs in disseminations, stringers and massive lenses (<1×8 metres). Chromium oxide grades are highly variable (13 to 35 weight per cent Cr_2O_3) with Cr/Fe ratios of about 2. The Scottie Creek deposit has yielded approximately 540 tonnes of ore averaging more than 22 weight per cent Cr_2O_3 (Hancock, 1990a) and has been used as a type example of podiform chromite (Eckstrand, 1984).

The Anarchist, Bridon, Rock Creek, and Chrome Ridge occurrences in south-central British Columbia are found in the Permo-Carboniferous Anarchist and correlative Chapperon Groups that belong to the Okanagan subterrane of Quesnellia and were formed in an oceanic or marginal-basin setting (Hancock, 1990a). The chromite deposits are hosted by serpentinite, relict dunite or harzburgite, and have textural and structural features similar to the podiform chromitites already described (Figure 6-7). Assay samples record 28 to 42 weight per cent Cr_2O_3 and Cr/Fe ratios between 1.8 and 3.2; heavy mineral concentrates typically yielded less than 0.1 gram per tonne platinum.

Other minor showings of note (Figure 6-5) are: Anvil Chrome hosted by the Blue River ultramafite that was obducted in the Jurassic and forms part of the Sylvester allochthon (Nelson and Bradford, 1989); and disseminated to massive chromite in dunite layers enclosed by harzburgite which form part of the Shulaps ophiolite complex (Schiarrizza *et al.*, 1989; Calon *et al.*, 1990). Chromite occurrences of the Alpine-type also occur in combination with sulphides at Rossland and Mastadon. In 1918, the latter deposit produced some 607 tonnes of chromite

ore averaging 38.5 weight per cent Cr_2O_3 but nickel has been the focus of attention since the mid-1960s (Hancock, 1990a).

NICKEL

Ultramafic-mafic rocks and their chemical degradation products are the major source of world nickel supplies and a significant future resource. Magmatic sulphides have been, and continue to be, the major producers (Figure 6-8) with Canada (*e.g.*, Sudbury and Manitoba Nickel Belt) and the U.S.S.R. (*e.g.*, Pechenga, Noril'sk-Talnakh) leading world production figures (Table 6-4). Industrial uses for nickel are primarily in the production of stainless steels and alloys, and electroplating.

NICKEL DEPOSIT MODEL

Most of the world's economic concentrations of magmatic nickel-copper sulphides are hosted by Precambrian ultramafic-mafic lavas (komatiites-

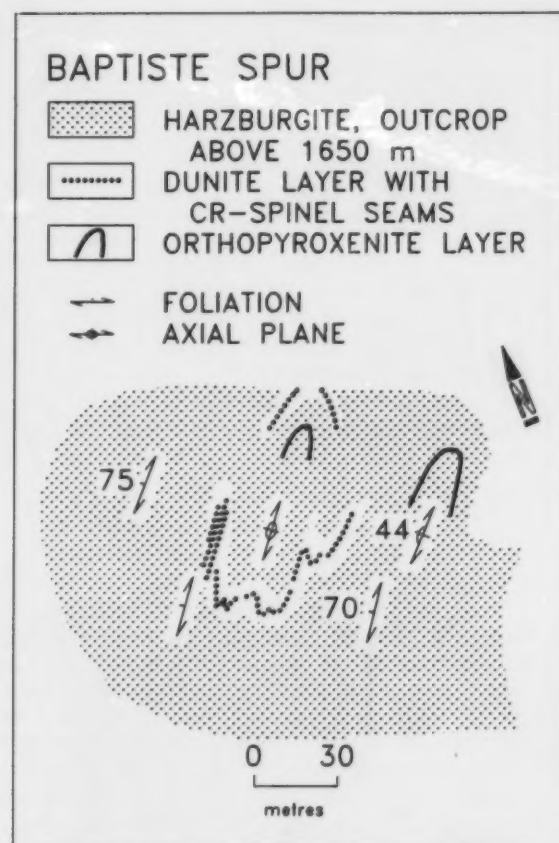


Figure 6-6. Detailed geology of chromite layers in dunite at Baptiste Spur in Mount Sidney-Williams Alpine-type peridotite, central British Columbia (after Whittaker and Watkinson, 1986).

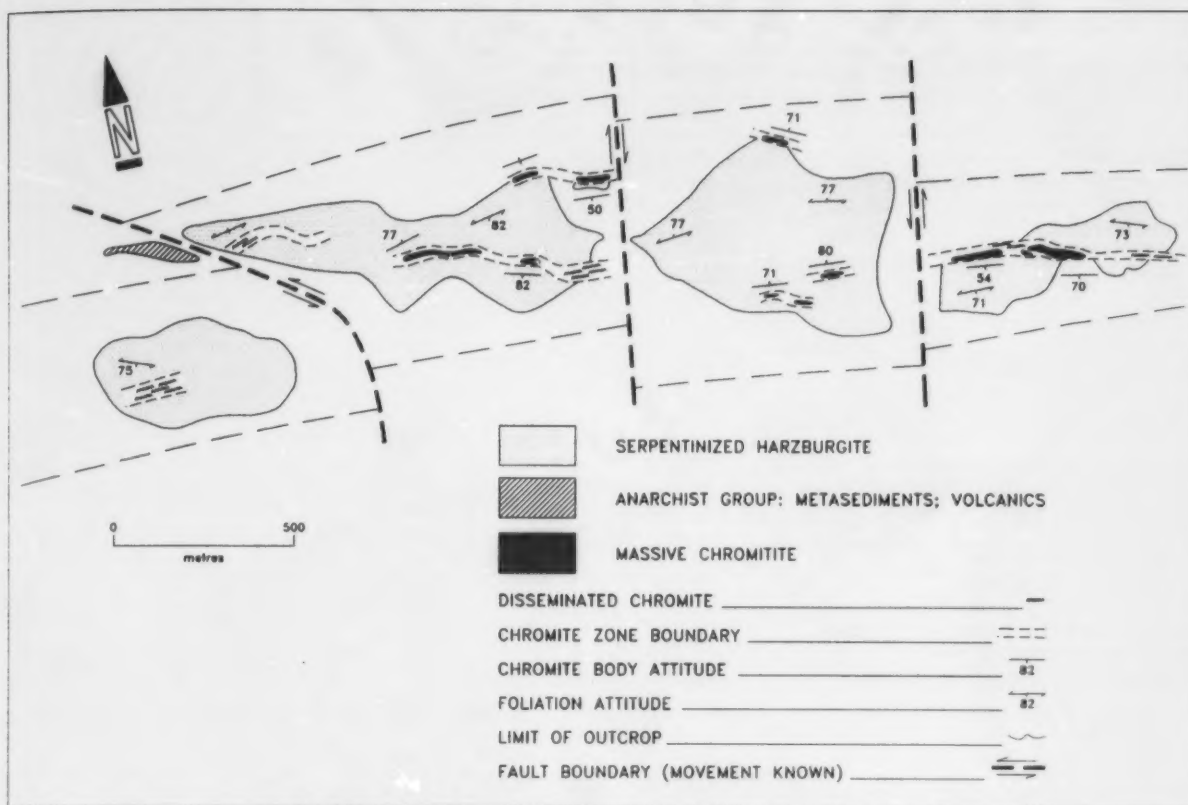


Figure 6-7. Geology of the Bridon chromite showings (after Whittaker, 1983).

tholeiites) and synvolcanic intrusions. The Sudbury igneous complex is an apparently unique exception that has been linked to meteorite impact. A comprehensive treatment of these and other magmatic sulphide deposits is given by Naldrett (1989).

Favourable geological environments for magmatic nickel-copper sulphides of potential economic importance in the Cordillera are essentially limited to Paleozoic-Mesozoic ophiolite complexes and ultramafic to gabbroic intrusions, of which the latter category would appear to have more potential. In terms of their inherent, although all too often poorly described, characteristics, nickel occurrences examined below probably relate to more than one deposit type. However, the most significant and best documented by far is the synorogenic-synvolcanic or gabbroid-associated Giant Mascot deposit (Table 6-1; also Eckstrand, 1984, deposit type 12.2c). The "gabbroid-associated" terminology is perhaps more apt where the timing of mineralization relative to spatially associated volcanism and regional deformation is not known. In general terms, the genesis of these deposits is related to the segregation and concentration of an immiscible sulphide melt from primitive silicate liquids derived by partial melting of the mantle. The ore minerals and textures are primarily determined during subsolidus crystallization of the

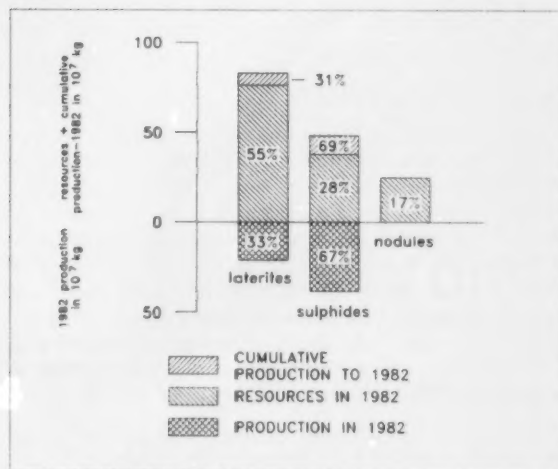


Figure 6-8. Resources and typical annual production of nickel in the three principal deposit types: magmatic sulphides, nickel laterites and deep-sea manganese nodules (after Naldrett, 1989).

sulphide melt, although later remobilization may play a significant role. Potentially important by-products are cobalt, gold and platinum-group elements, particularly as sulphides are efficient collectors of the noble metals.

TABLE 6-4

Nickel: World Mine Production, by Country¹ (Short tons of nickel content)

Country	1984	1985	1986	1987	1988 ^P	1989 ^E
Albania (content of ore) ^E	10 100	10 600	10 700	9 900	9 900	9 900
Australia (content of concentrate).....	84 793	94 531	84 590	82 182	68 738 ²	73 900 ²
Botswana (content of ore milled).....	24 126 ^R	28 991 ^R	28 173 ^R	28 572	28 628	28 700
Brazil (content of ore).....	25 940	18 158 ^R	23 262 ^R	22 215	22 963	23 100
Burma (content of speiss) ^E	22	60	52	55	115	110
Canada ³	191 499 ^R	187 361	180 381	208 431	240 917 ²	224 371
China ^E	15 400	27 600	27 600	27 600	27 600 ^R	27 600
Colombia (content of ferroalloys).....	24 124	17 013	20 975	21 301	18 300 ²	16 500
Cuba (content of oxide sinter sulphide).....	35 087 ^R	35 370	35 514	37 285	46 030	47 400
Dominican Republic.....	26 371	27 992	24 116	35 848	32 300 ^E	35 300
Finland (content of concentrate).....	7 626	9 421	13 102	11 637	12 897	13 200
Germany ^E	2 200	2 200	2 200	2 200	2 200	1 700
Greece (recoverable content of ore) ^E	18 400	24 300 ^R	15 900 ^R	10 100 ^R	9 900 ^R	9 900
Indonesia (content of ore) ⁴	52 474	44 463	59 171	63 674	63 914	70 900
New Caledonia (recoverable content of ore)....	64 293 ²	79 800	68 100	62 700	74 600	137 800
Norway (content of concentrate).....	358	468	483	440 ^E	440 ^E	440
Philippines.....	14 993	31 039	14 099	8 619	11 900 ^E	15 400
Poland (content of ore) ^E	2 300	2 200	2 200	2 200	2 000	2 000
South Africa Republic of ^E	27 600	27 600	34 200 ^R	37 800	38 400	39 100
U.S.S.R. (content of ore) ^E	192 000	204 000 ^R	215 000 ^R	226 000 ^R	237 000 ^R	237 000
United States (content of ore shipped).....	14 540	6 127	1 175	—	—	—
Yugoslavia (content of ore) ^E	4 100 ^R	4 200	4 200	4 300	4 300	4 200
Zimbabwe (content of concentrate) ^E	13 390	12 253 ²	4 100 ^R	6 900 ^R	8 300 ^R	8 800
Total	851 736^R	895 747^R	869 293^R	909 959	961 342	1 027 321

^E Estimated ^P Preliminary ^R Revised Data from Nickel Minerals Yearbook 1988 and 1989 (1989-1990).¹ Insofar as possible, this table represents recoverable mine production of nickel. Where actual mine output is not available, data related to a more highly processed form have been used to provide an indication of the magnitude of mine output, and this is noted parenthetically or by a footnote following the country name. Table includes data available through May 4, 1989.² Reported figure.³ Refined nickel and nickel content of oxides and salts produced, plus recoverable nickel in exported matte and speiss.⁴ Includes a small amount of cobalt not reported or recovered separately.

NICKEL OCCURRENCES

There are relatively few nickel occurrences associated with ultramafic-mafic rocks in British Columbia and no currently active mines (Figure 6-5). Most known occurrences are distributed in the southern part of the province and have been subdivided according to their immediate hostrocks. Most of these deposits may be classed as accretionary or pre-accretionary. One unusual example of magmatic sulphides in an Alaskan-type ultramafic intrusion, the Turnagain River complex, is discussed later in relation to PGE environments.

The largest single past producer of nickel is the Giant Mascot (Pacific Nickel or Pride of Emory) mine (1958-1974). It produced 26.8 million kilograms of nickel and 14 million kilograms of copper by milling 4.2 million tonnes of ore from 26 distinct ore bodies, maintaining an average millhead grade of 0.77 weight per cent nickel, 0.33 weight per cent copper, 0.68 gram per tonne gold and 0.34 gram per tonne platinum-group elements (Christopher and Robinson, 1975; Hancock, 1990a). Maximum ore grades were quoted as: 2.6 weight per cent nickel, 0.9 weight per cent copper, 1.0 weight per cent chro-

mium, 0.1 weight per cent cobalt, 0.68 gram per tonne gold, 2 grams per tonne platinum, and 7.2 grams per tonne palladium. Ore reserves estimated prior to mine closure are presently being re-evaluated.

The nickel-copper ores are hosted by a stock-like body (1.5 by 3 km) of ultramafic rocks that are considered to represent the earliest phase of the predominantly dioritic Spuzzum pluton (McLeod *et al.*, 1976; Monger, 1989; Figure 6-9). The pluton was emplaced by multiple intrusion between about 120 to 90 Ma, approximately coincident with a major early Late Cretaceous accretionary event in the Cordillera. The Giant Mascot deposit now sits within a thrust stack of eastward-dipping, westward-verging terrane slices of uncertain protolith (Monger, 1989).

The ultramafic lithologies exhibit cumulus textures and are crudely zoned about cores of peridotite (and minor dunite) enveloped by pyroxenites (websterite, olivine websterite and orthopyroxenite; Figure 6-1) and succeeded outwards by hornblende pyroxenite and hornblende. The ore shoots are steeply dipping pipe-like bodies containing massive to disseminated

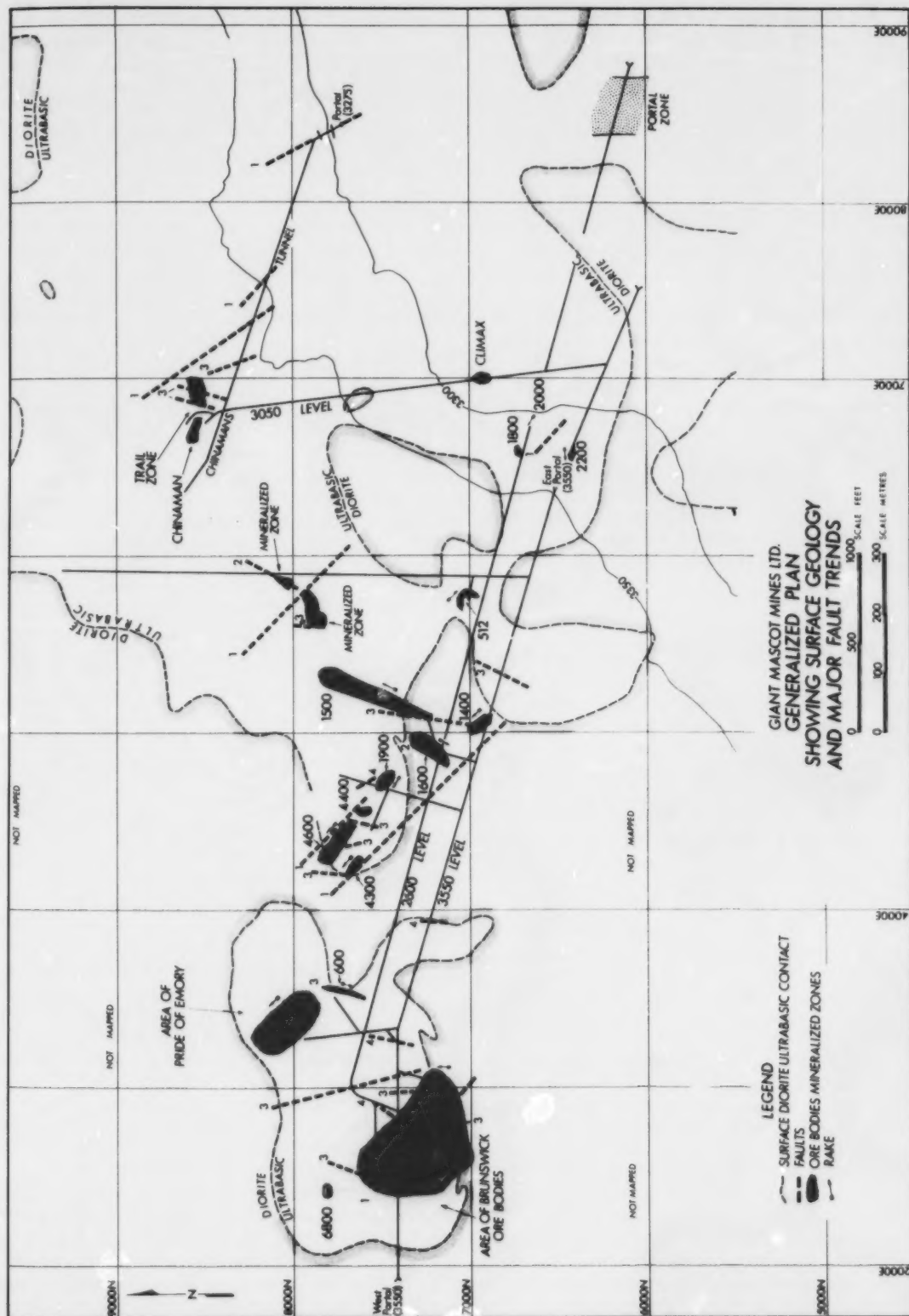


Figure 6-9. Generalized geology of Giant Mascot mine near Hope, British Columbia, showing distribution of nickel-copper orebodies (after Christopher and Robinson, 1975).

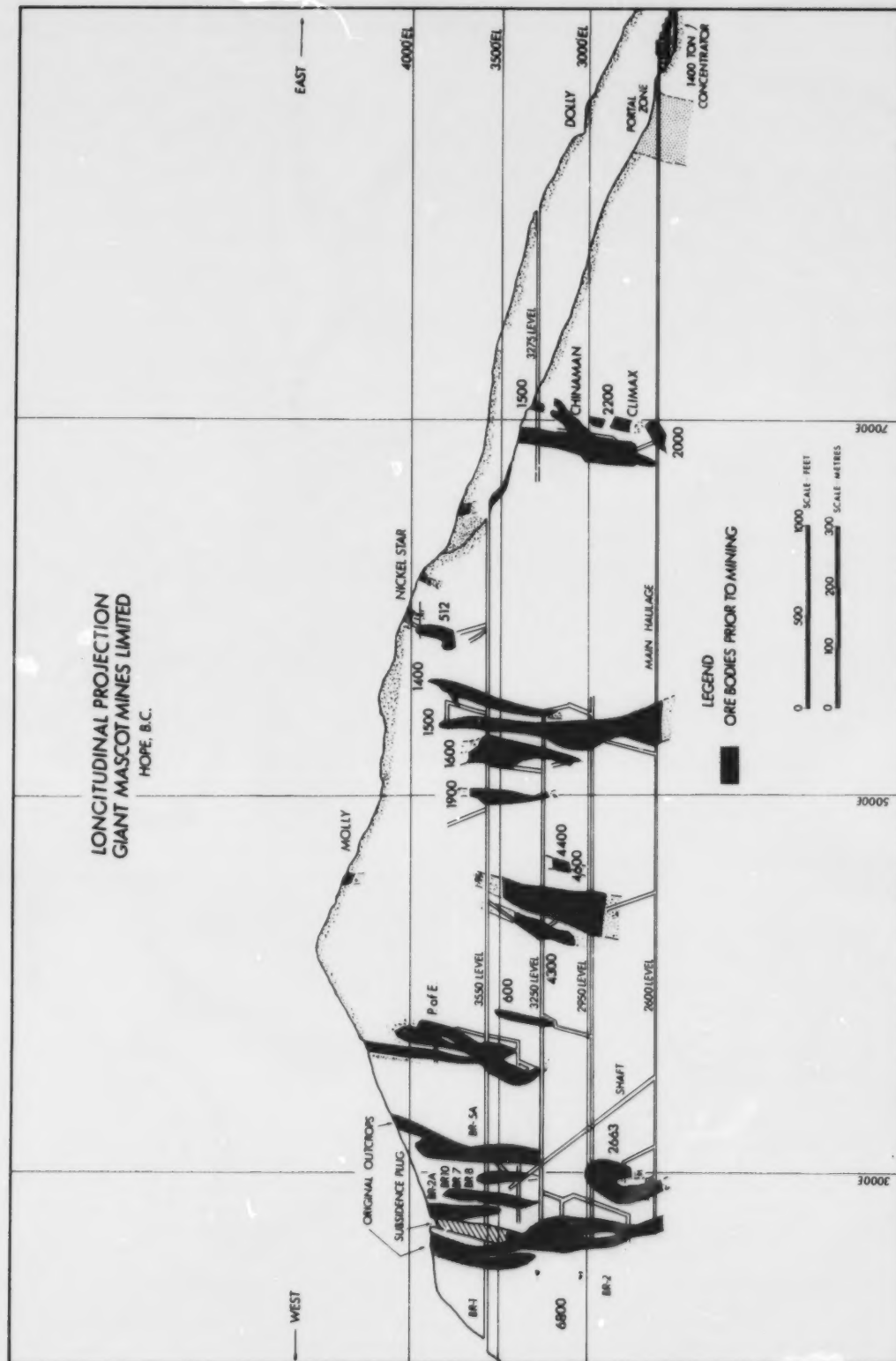


Figure 6-10. Cross-section of Giant Mascot mine showing steeply dipping ore pipes
(after Christopher and Robinson, 1975).

ore that may be concentrically zoned around a peridotite core (Figure 6-10). The principal ore minerals are pyrrhotite, pentlandite and chalcopyrite that commonly exhibit net-textures involving unaltered cumulate silicates. Detailed studies of ore mineralogy, chemistry and textures (Aho, 1956; McLeod, 1975; Muir, 1971) have substantiated an origin via magmatic segregation and accumulation of an immiscible sulphide melt.

The Settler and Diaoff Creek sulphide showings were discovered in an attempt to extend the life of the Giant Mascot mine. They comprise weakly disseminated pyrrhotite and minor chalcopyrite, in part fracture-controlled, hosted by pyroxenite and peridotite. Assays have yielded 0.19 to 0.22 weight per cent nickel and trace copper.

The second largest known nickel-copper occurrence of the gabbroid-associated type is the E&L deposit at Nickel Mountain near the western margin of Stikinia (Hancock, 1990b). A sulphide-rich olivine gabbro stock intrudes metavolcanic and metasedimentary rocks of the Lower Jurassic Hazelton Group. The intrusion appears to predate mid-Cretaceous regional deformation and is thus not rigorously syn-orogenic. However, associated plugs and a dike swarm indicate that the Nickel Mountain stock is most likely synvolcanic. Magmatic sulphides, chiefly pyrrhotite, pentlandite and chalcopyrite with trace siegenite, pyrite and magnetite, form veins, disseminations and massive lenses confined to the central stock. The main ore zones are steeply-dipping pipes that extend to a depth of over 200 metres. Published reserves comprise 2.9 million tonnes of 0.8 weight per cent nickel, 0.62 weight per cent copper, 6.8 grams per tonne silver and 0.34 gram per tonne gold. Grab samples of mineralized rock run up to 400 parts per billion platinum and 415 parts per billion palladium (Hancock, 1990b).

In comparison to the deposits described above, other ultramafic-associated nickel occurrences are minor. Most are associated with fragmented ophiolite complexes and are poorly documented (Hancock, 1990a). The Old Nick and Mastadon nickel showings are hosted by the Anarchist Group of the Okanagan subterrane as described earlier; the Sovereign occurrence lies within the Crooked Amphibolite and the Rossland is hosted by the Pennsylvanian Mount Roberts Formation of the Slide Mountain Terrane. Nickel generally occurs in disseminated pentlandite, millerite and heazlewoodite. The mineralization is typically low grade with a range of about 0.20 to 0.45 weight per cent nickel. These occurrences are probably hydrothermal in origin.

Mineralization at the Tofino nickel-copper sulphide main showing is hosted by a thin amphibolitized mafic sill in the Paleozoic Sicker Group, a metavolcanic and metasedimentary rock package of island-arc affinity in Wrangellia (Figure 6-5). The sulphides occur as disseminations or small massive lenses of predominantly pyrrhotite, pentlandite,

chalcopyrite and pyrite (Hancock, 1990a). Grades from grab samples reach 3.5 weight per cent nickel, 3.6 weight per cent copper, 48 grams per tonne silver, and up to 6.2 grams per tonne palladium with minor platinum and trace gold (Eastwood, 1963). The palladium:platinum ratio runs about 5:1 and the main repository of palladium appears to be merenskyite ($\text{Pd}(\text{Te},\text{Sb})_2$).

PLATINUM-GROUP ELEMENTS

The platinum-group elements (PGE) – osmium, iridium, ruthenium, rhodium, platinum and palladium, listed in decreasing order of their melting points – are strategic metals. Their physical and chemical properties render them ideally suited for a variety of electronic (thermocouples, fuel cells) and medical uses as well as their more familiar role as catalytic converters in automobile emission-control systems. The major producers of PGE are South Africa (Bushveld Complex) and the U.S.S.R. (largely Noril'sk-Talnakh and placers) with Canada a distant third (Sudbury nickel-copper ores; Tables 6-5 and 6-6). World-class economic deposits generally have an average grade of total PGE of 5 to 20 grams per tonne (or ppm). More than 80 per cent of total world reserves are contained in the Bushveld Complex.

PGE DEPOSIT MODELS

Many detailed summaries of the geologic settings of world-wide PGE occurrences have been published of late, spurred in part by recently renewed interest from the exploration community (e.g., Hulbert *et al.*, 1988; Buchanan, 1988; Prichard *et al.*, 1988; and see Macdonald, 1988 for a brief review, and Naldrett, 1989, Chapter 5 for the characteristics of major stratiform PGE deposits). Platinum-group element environments and occurrences in the Cordillera have also been the subject of recent open file compilations by Evenchick *et al.* (1986) and Rublee (1986). The wide range of orthomagmatic PGE environments may be subdivided according to whether the PGE typically occur as a dominant commodity, or as a co-product or by-product (Cabri, 1982). The latter category is represented by the podiform (ophiolitic) chromite and magmatic nickel-copper sulphide (Merensky-type) ores of large stratiform complexes (e.g., Bushveld, Stillwater, Great Dyke, Munni Munni and Penikat intrusions) and the former categories by the Alaskan-type intrusions and layered chromitites in stratiform complexes (Table 6-7). Platinum-group elements in ophiolite settings in British Columbia are known to occur (in chromitites), but total PGE abundances in published data rarely exceed 500 parts per billion and osmium, iridium and ruthenium are typically enriched relative to rhodium, platinum and palladium (Talkington and Watkinson, 1986). Such occurrences are not of economic significance in present-day markets.

TABLE 6-5

World Production of Platinum Group Metals (1984-88)

	1984	1985	1986	1987	1988 ^P
(tonnes)					
EUROPE					
Finland					
Palladium.....	34	35	96	89 ^E	93
Platinum.....	33	35	120	120 ^E	124
Yugoslavia ^E					
Palladium.....	96	103	96	100	100
Platinum.....	6	8	8	3	3
Subtotal.....	169	181	320	312	320
AFRICA					
Ethiopia ^E					
Placer platinum.....	4	5	5	5	5
South Africa					
Platinum group metals.....	108 862	115 000	123 000	131 257	133 278
Zimbabwe					
Palladium.....	38	30	35	29	31
Platinum.....	24	19	26	18	19
Subtotal.....	108 928	115 054	123 066	131 308	133 333
ASIA					
Japan					
Palladium.....	1 051	1 359	1 453	1 417	1 197
Platinum.....	607	691	663	753	650
Subtotal.....	1 658	2 050	2 116	2 170	1 848
AMERICA					
Canada					
Platinum group metals.....	10 369	10 534	12 190	10 930	12 541
Colombia					
Placer platinum.....	314	362	447	638	815
United States					
Placer platinum and platinum group metals.....	455	w	w	w	w
Subtotal.....	11 138	10 896	12 637	11 568	13 356
AUSTRALIA					
Palladium.....	523	476	428	491	411
Platinum.....	66	95	115	131	106
Subtotal.....	589	571	543	622	516
EASTERN COUNTRIES					
U.S.S.R. ^E					
Placer platinum and platinum group metals.....	115 000	118 000	120 000	121 000	121 000
World Total.....	237 482	246 752	258 682	266 980	270 373

Source: Energy, Mines and Resources, Canada.

^P Preliminary^E Estimate^w Withheld to avoid disclosing company proprietary data; excluded from "Total".

Data taken from Canadian Minerals Yearbook 1988 and 1989 (1989b, 1990).

TABLE 6-6

Relative Proportions, Grade (g/tonne) and Identified Resources (10⁴ g) of PGE in Major Deposits

	Bushveld Complex						Noril'sk-Talnakh U.S.S.R.		Stillwater J-M Reef		Great Dyke		Sudbury Canada		Colombia		Total Resources
	Merensky Reef		UG-2		Plat. Reef		Prop	Res	Prop	Res	Prop	Res	Prop	Res	Prop	Res	
	Prop	Res	Prop	Res	Prop	Res											
Pd.....	25	4 371	35	11 315	46	5 425	71	4 402	66.5	713	37.1	2 936	40	112	1		29 274
Pt.....	59	10 323	42	13 547	42	4 960	25	1 550	19	217	52.8	4 130	38	105	93		34 925
Rh.....	3	527	8	2 573	3	372	3	186	7.6	84	4.7	367	3.3	<31	2		4 109
Ru.....	8	1 395	12	3 875	4	465	1	62	4.0	43	4.7	367	2.9	<31	—		6 207
Ir.....	1	186	2.3	744	0.8	93	—	—	2.4	<31	0.6	46	1.2	<31	3		1 069
Os.....	0.8	155	—	—	0.6	62	—	—	—	—	0.6	46	1.2	<31	1		263
Grade in g/tonne																	
total PGE.....	8.1		8.71		7.27		3.8		22.3		4.7		0.9				
Total resources	16 957		32 054		11 377		6 200		1 057		7 892		217				

Prop = proportion; Res = reserves. Data taken from Naldrett (1989).

Alaskan-type complexes and their associated placers appear to be the most favourable environments for PGE in the Cordillera (Table 6-1, Models 9 and 39b). Based on mineralogical differences in the lode occurrences, three subtypes of PGE deposits are known, all of which contain discrete platinum-group minerals: the chromitite-PGE association hosted by dunite is the most important and widespread; the magnetite-PGE subtype is known from at least two complexes in British Columbia and northern California (Table 6-1) and is hosted by hornblende-bearing clinopyroxenites; and in a newly recognized subtype from Australia, the PGE are associated with pegmatitic clinopyroxenites or "P-units" (Johan *et al.* (1989). In all three associations, base metal sulphides are of little importance.

Although poorly dated isotopically, it appears that Alaskan-type intrusions in British Columbia and their associated PGE mineralization are pre-accretionary, and some may have formed prior to amalgamation of the Intermontane Superterrane. The following sections describe the salient features of Alaskan-type complexes in British Columbia, and the nature and origin of PGE mineralization in lode and placer occurrences.

ALASKAN-TYPE COMPLEXES

Occurrences of the major Alaskan-type complexes in British Columbia are shown in Figure 6-11. Other smaller bodies are known to occur in the northern part of the province, predominantly in the Wrede-Polaris region. Their distribution is closely associated with Late Triassic to Early Jurassic arc volcanic rocks with which they have been genetically linked (Murray, 1972; Irvine, 1974b, 1976; Mortimer, 1986). The geological environment of PGE mineralization in these Alaskan-type complexes is illustrated by reference to the Polaris, Wrede and Tulameen intrusions.

The Polaris complex (45 square kilometres) is one of the largest and best-exposed Alaskan-type intrusions in British Columbia (Nixon *et al.*, 1990b; Figures 6-12 and 6-13). It forms a westward-facing, westward-dipping transgressive sill (>14 by <4 kilometres) that intrudes a homoclinal sequence of metavolcanic and metasedimentary island-arc rocks which are considered to form the basement of Quesnellia (Lay Range assemblage, Harper Ranch subterrane). A metamorphic aureole of lowermost amphibolite grade is overprinted by greenschist facies assemblages in rocks that host the intrusion. All typical Alaskan-type lithologies are represented: dunite, chromitite, wehrlite, olivine clinopyroxenite, clinopyroxenite, hornblende clinopyroxenite, hornblendite, and hornblende gabbro, and more leucocratic feldspathic pegmatite that locally contains quartz. Cumulate textures are widespread and well preserved. The presence of cumulus and intercumulus phlogopite in early differentiates (dunite) is a distinctive petrological feature.

The internal stratigraphy of the complex is well exposed in cross section (Figure 6-13). Dunite forms most of the lower part of the intrusion, and, in a general sense, is succeeded upward by thickly stratified wehrlitic cumulates and clinopyroxenite, hornblende clinopyroxenite and hornblendite, and gabbroic rocks which are well developed at the roof of the complex. Contacts between these major units are sharp to gradational, and none of these lithologies display the spectacular layering that is so common in the Duke Island complex (Irvine, 1974a). On a local scale, evidence exists for complex multiple intrusive events between wehrlitic and pyroxenitic lithologies, and between gabbro and hornblendite. In addition, disrupted layers and blocks (typically less than 0.5 metre across) of previously consolidated chromitite, and complex zones of intermixing of wehrlitic and clinopyroxenitic rocks, point to syndepositional remobilization of

TABLE 6-7

PGE-dominant Deposits

Deposit Types	Petro-Tectonic Features	PGE Distribution	Remarks
1. Merensky Type a. Bushveld Complex b. Stillwater Complex* c. Great Dyke d. Munni Munni Complex e. Penikat Intrusion	Very large bodies of basaltic magma. Usually intruded into stable continental rocks. Layering prominent with PGE restricted to layers 10-200 cm thick.	Major PGM variable: include Pt, Pd, Ru, sulphides, Pt-Fe alloys, and sperrylite, Pd-Pt tellurides locally more abundant. Measurable Pd solid solution in pentlandite.	PGE grades 3-20 ppm. PGE recoveries 75%. Ni & Cu major by-products: Au, Ag minor. Merensky reef in Bushveld, and Stillwater J-M reef only producers, all others under active or intermittent investigation.
2. Layered Chromitites a. Bushveld Complex b. Stillwater Complex	Petrotectonic setting as for Merensky type.	Major PGM include: PGE, sulphides, and Pt-Pd alloys.	PGE grades comparable to Merensky type or richer. Production from UG-2 layer in Bushveld.
3. Alaskan or Zoned Type and Derived Placers a. Urals b. Alaska Panhandle c. Goodnews Bay d. Cordillera e. Aldan Shield f. Colombia g. Ethiopia	Moderate size. Zoned ultramafic complexes intruded in: (i) active orogenic zones, Nizhnii Tagil (Ural) sub-type (ii) stable platform, Inagli (Aldan) sub-type. May have dunite core surrounded by successive shells of olivine clinopyroxenite, magnetite-rich clinopyroxenite, and hornblende. Calcic clinopyroxene, Fe-rich chromite and no orthopyroxene or plagioclase.	Major PGM are Pt-Fe alloys, followed by Pt-Ir alloys. Very irregular PGE distribution. Close association with chromite.	PGE production mainly from derived placers. PGE grades for dredging estimated at 0.3-3 ppm/m ³ . Sparse information on PGE bedrock production from U.S.S.R. Chromium by-product?

* Original tectonic setting unclear (modified from Cabri, 1982).

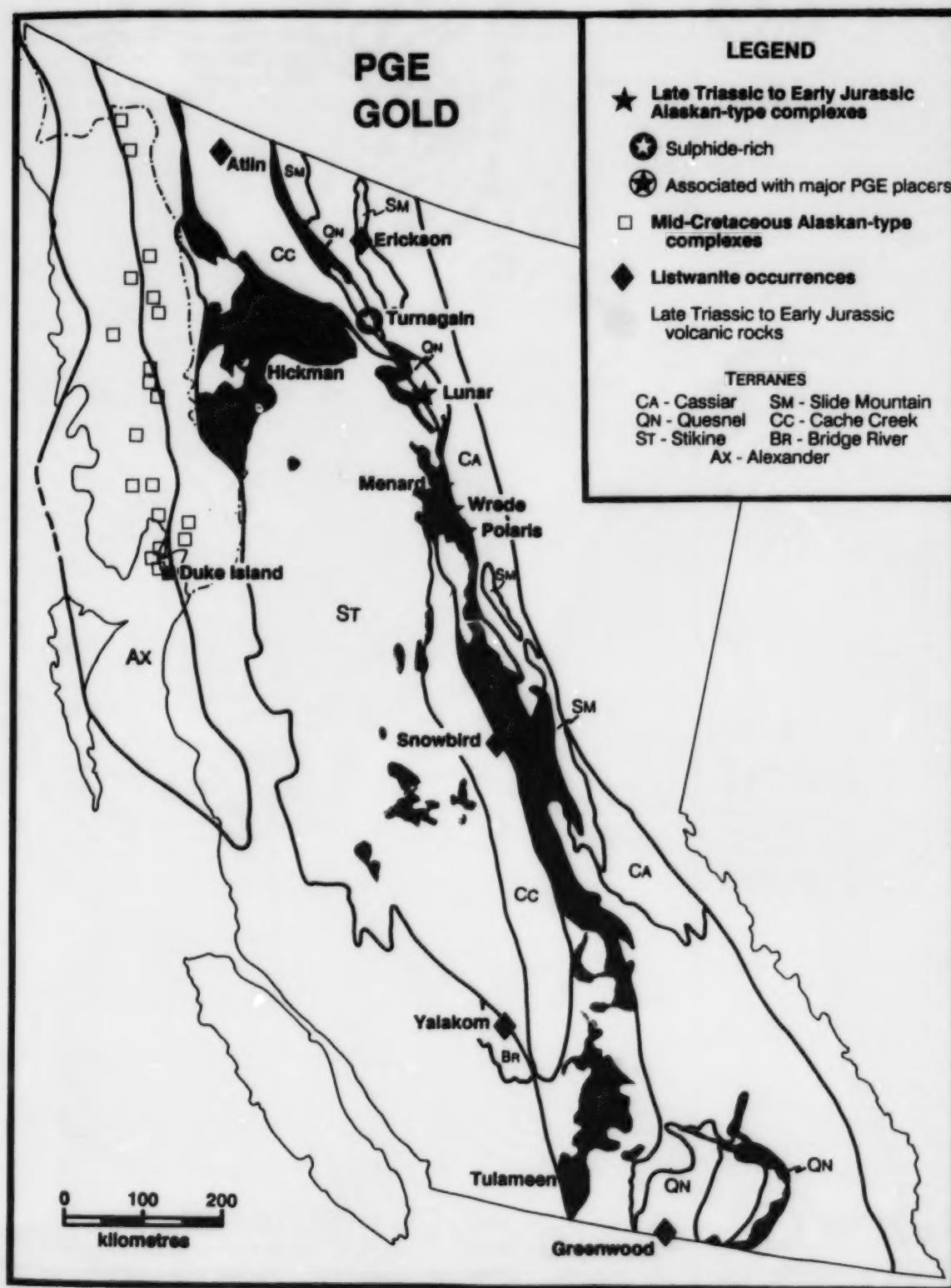
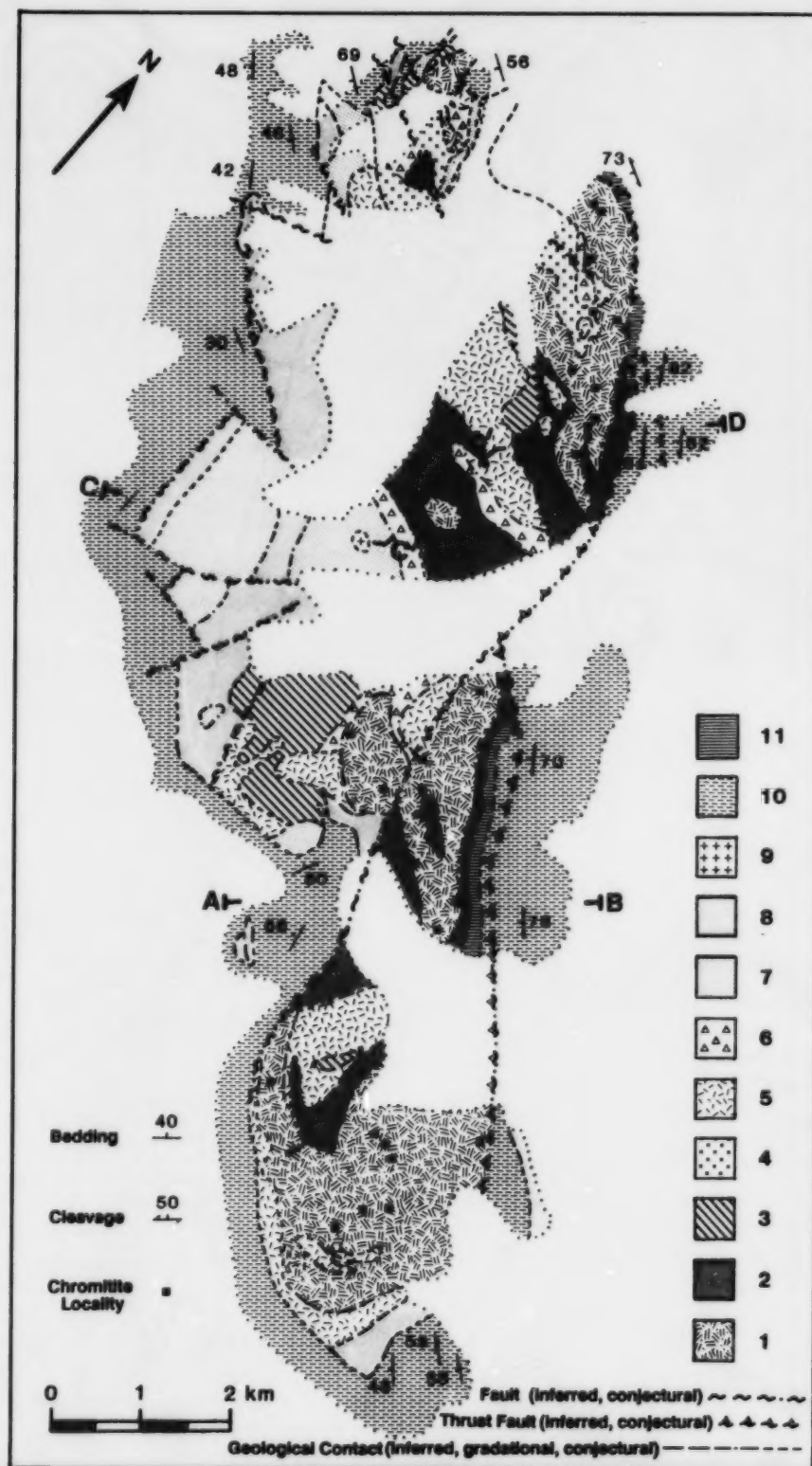


Figure 6-11. Occurrences of major Alaskan-type complexes and listwanite localities in British Columbia and their tectonostratigraphic setting.

Figure 6-12. Generalized geology of the Polaris Alaskan-type complex, north-central British Columbia (modified after Nixon et al., 1990b). Key to map units: 1, dunite; 2, olivine wehrlite; 3, wehrlite; 4, undifferentiated olivine wehrlite and wehrlite; 5, olivine clinopyroxenite and clinopyroxenite; 6, mixed clinopyroxenitic and wehrlitic unit with minor dunite; 7, hornblende clinopyroxenite, clinopyroxene hornblendite, hornblendite and minor gabbro; 8, gabbroic rocks; 9, syenite/leucomonzonite; 10, metasedimentary and metavolcanic rocks of the Lay Range assemblage (Harper Ranch tectonostratigraphic terrane); 11, variably sheared basal hornblende gabbro, clinopyroxenite and amphibolite. A-B and C-C'-D'-D indicate location of cross-sections shown in Figure 6-13.



early cumulates by slumping and density flow processes operating within the magma chamber. The fragmentation and redistribution of chromite cumulate horizons have important implications for the economic potential of PGE mineralization in this environment (discussed below).

A basal ductile fault zone exposed near the eastern margin of the intrusion contains kinematic indicators which suggest that the complex has been tectonically uprooted and transported eastward together with its immediate hostrocks. This deformation is related to the mid-Jurassic collision of Quesnellia, situated at the eastern margin of the Intermontane Superterrane, with the ancestral North American continental margin.

Further north, the Wrede Creek complex, a much smaller Alaskan-type intrusion, has been described by Hammack *et al.* (1990) (Figure 6-14). A crude zonal arrangement of rock types is again apparent, ranging from dunite in the core through clinopyroxenite to hornblende and hornblende gabbro at the margin. However, in marked contrast to Polaris, wehrlitic lithologies are poorly developed. Hostrocks of the Late Triassic Takla Group are metamorphosed to amphibolite grade near intrusive contacts, and diamond drilling at the periphery of the intrusion indicates a stock-like body at depth. As in the case of Polaris, chromitite typically occurs as erratically distributed small pods and schlieren within the dunite.

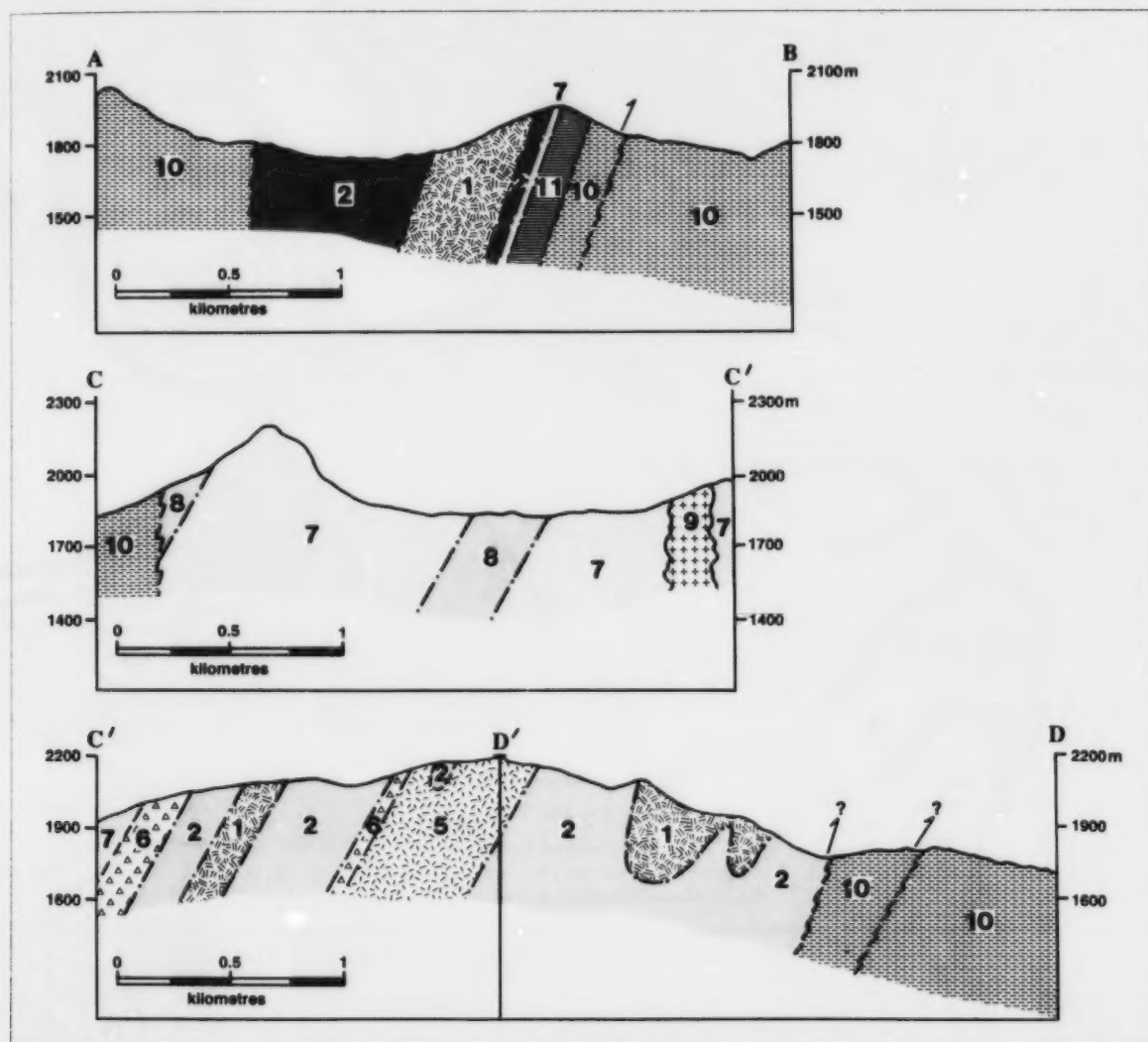


Figure 6-13. Schematic geological cross-sections of the Polaris complex (modified from Nixon *et al.*, 1990b). See Figure 6-12 for locations. Note addition of thin hornblende clinopyroxenite unit in section A-B.

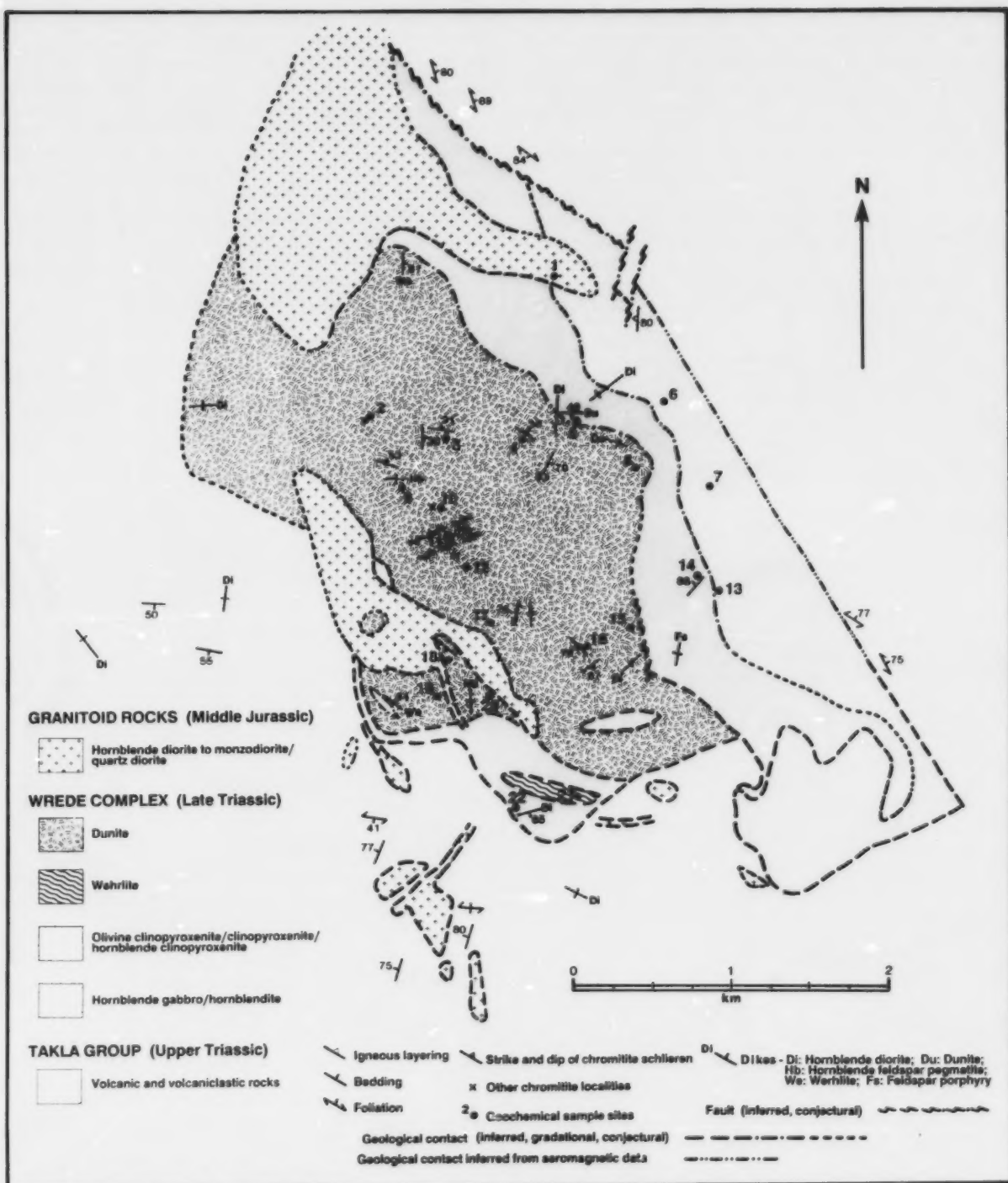


Figure 6-14. Generalized geology of the Wrede Creek Alaskan-type complex, north-central British Columbia (after Hammack et al., 1990).

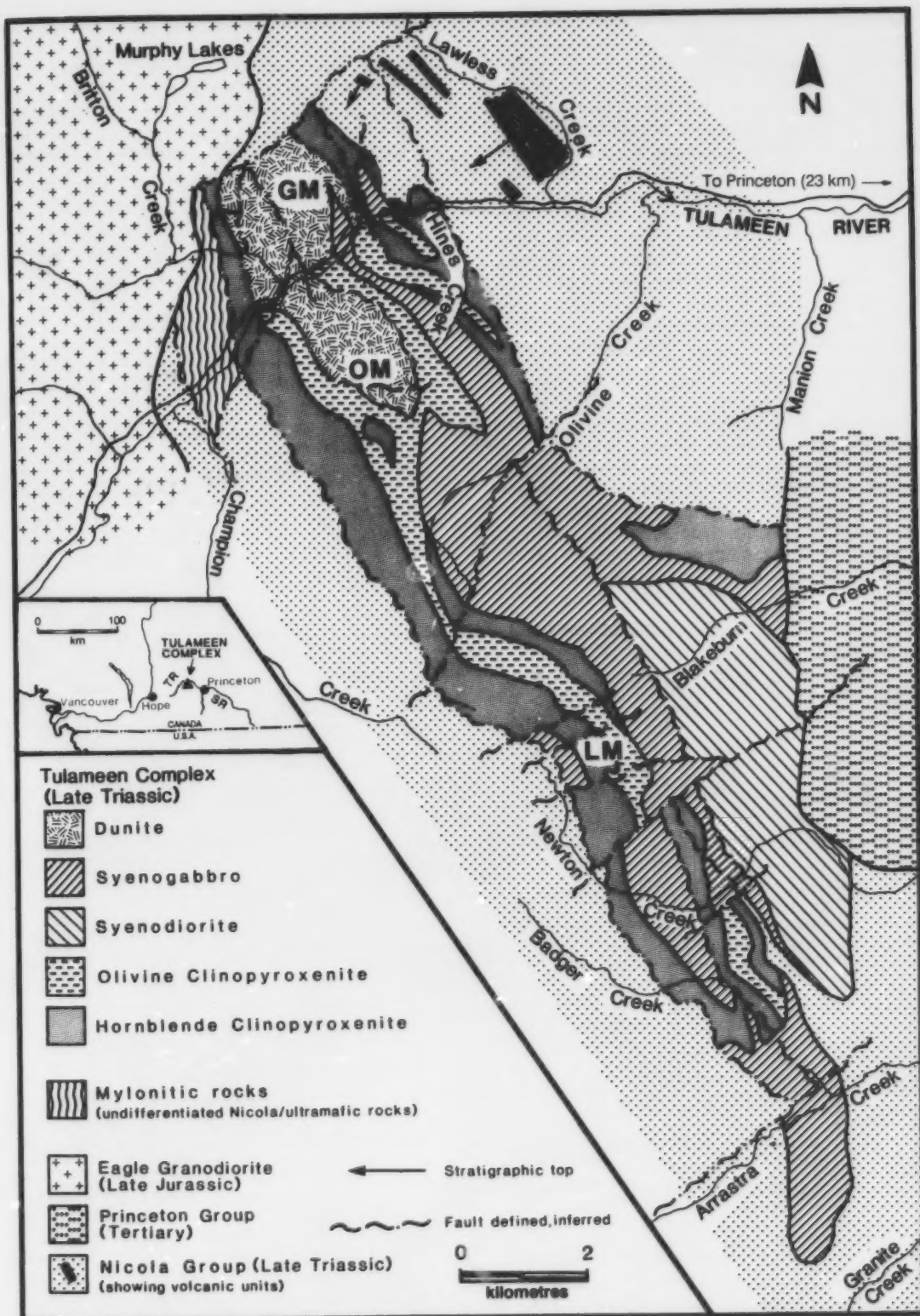


Figure 6-15. Generalized geology of the Tulameen Alaskan-type complex, south-central British Columbia (modified after Findlay, 1963). GM, Grasshopper Mountain; OM, Olivine Mountain; LM, Lodestone Mountain.

The Tulameen complex (60 square kilometres) is the most extensively studied Alaskan-type intrusion in the province (Findlay, 1963, 1969; St. Louis *et al.*, 1986; Nixon and Rublee, 1988; Nixon *et al.*, 1990a; Figure 6-15). It forms an elongate body (strike length 20 kilometres) emplaced within, and considered coeval with, westerly dipping, westward-facing metavolcanic and metasedimentary rocks of the Late Triassic Nicola arc. The complex is bounded by major mylonitic fault zones subparallel to the regional foliation. However, penetrative deformation within the complex is localized and cumulate textures are generally well preserved. Regional deformation and metamorphic grade increase west of the complex toward the western margin of Quesnellia, reflecting Cretaceous accretion of outboard terranes of the Coast Belt.

The principal rock types resemble those of the Polaris complex with the exception that wehrlitic units are not well developed. The variably serpentinized dunite "core" at the northern end of the complex is surrounded by olivine clinopyroxenite to clinopyroxenite and hornblende clinopyroxenite. The main mass of gabbroic rocks, syenogabbro to syenodiorite, is distributed eccentrically to the southeast. In the Tulameen River bed, units comprising chaotic mixtures of semiconsolidated blocks of

olivine clinopyroxenite and dunite cumulates, similar to the mixed wehrlite-clinopyroxenite zones at Polaris, are intercalated with thinly layered hornblende gabbros or diorites. These structures indicate periodic slumping of early-formed cumulate sequences and redeposition by mass flowage at lower levels in the magma chamber.

Remobilization is also evident in the dunite core where massive to heavily disseminated chromite forms pods, nodules and schlieren, or irregularly and complexly folded layers. The largest chromitite

TABLE 6-8

Abundances* of Platinum-group Elements in Chromitites of the Tulameen Complex

Sample	Pt	Pd	Rh	Ru	Ir	Os
GN87-146 ¹	2500	5	20	<10	17	8
GN87-146 ²	9297	73	—	—	—	—
GN87-146 ³	3189	23	—	—	—	—
GN87-147 ¹	5600	75	56	<5	140	20
GN87-147 ²	7953	59	—	—	—	—
GN87-147 ³	5527	47	—	—	—	—
GN87-147 ³	5380	39	(duplicate subsample)			
GN87-147 ⁴	8348	<30	70	<15	243	50
GN87-148 ¹	5300	12	67	50	220	25
GN87-148 ³	4762	19	—	—	—	—
GN87-148 ⁴	7398	<15	68	<20	247	48
Average	3410	<83	40	—	100	40
Chromitite**	(2220)		(20)		(40)	(20)

* Concentrations in ppb.

— not determined.

Analyses made on 50 g splits of rock powder using fire-assay preconcentration of noble metals followed by:

¹ Instrumental neutron activation (Activation Laboratories Ltd., Ancaster, Ontario)

² Atomic absorption spectrometry — graphite furnace finish (Analytical Laboratories, B.C. Ministry of Energy, Mines and Petroleum Resources, Victoria, British Columbia)

³ Inductively coupled plasma mass spectrometry (Geochemical Laboratories, Geological Survey of Canada, Ottawa)

⁴ Instrumental neutron activation (Institut National de la Recherche Scientifique, Georesources, Sainte-Foy, Quebec)

** Mean value (standard error of the mean in parentheses) from St. Louis *et al.*, 1986, Table 4.

Sample locations: GN87-146: 230 m NW of Grasshopper Mountain summit at 1420 m (Lat. 49°32.7'N, Long. 120°53.9'W); GN87-147: southern slope of Grasshopper Mountain at 1370 m (Lat. 49°32.3'N, Long. 120°54'W); GN87-148: 740 m SSW of Grasshopper Mountain summit at 1340 m (Lat. 49°32.2'N, Long. 120°54'W).

TULAMEEN

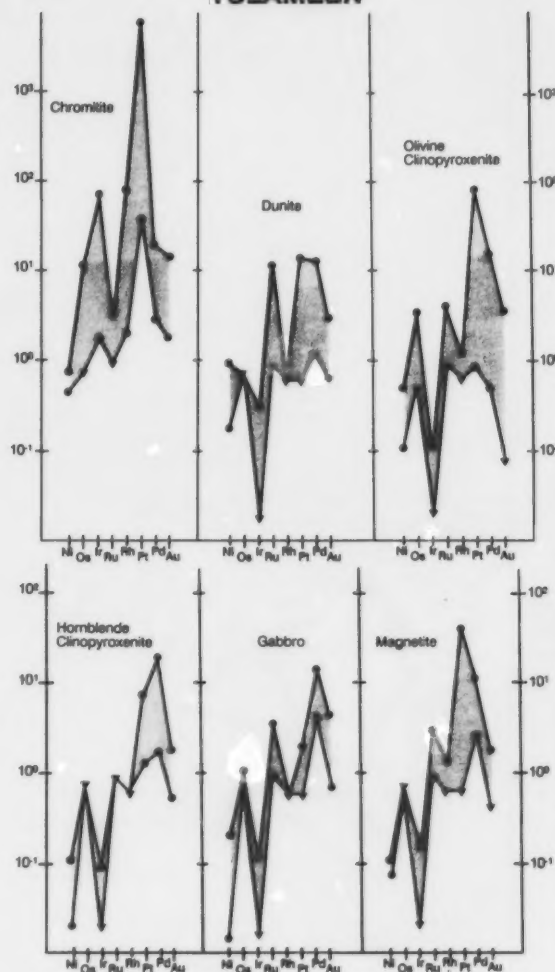


Figure 6-16. Range of normalized noble metal patterns in major rock types of the Tulameen complex. Normalizing values are mantle abundances (C1 chondrite $\times 0.00815$ except Ni) from Barnes *et al.* (1988) given in parts per billion unless otherwise indicated: Ni, 2000 parts per million; Os, 4.2; Ir, 4.4; Ru, 5.6; Rh, 1.6; Pt, 8.3; Pd, 4.4; and Au, 1.2. Inverted triangles are values below detection limits.

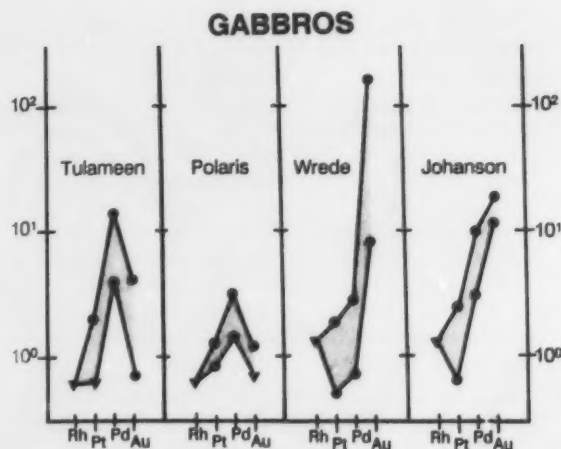


Figure 6-17. Range of normalized noble metal patterns in gabbroic rocks of Alaskan-type complexes in British Columbia. Normalizing values and symbols are those used in Figure 6-16.

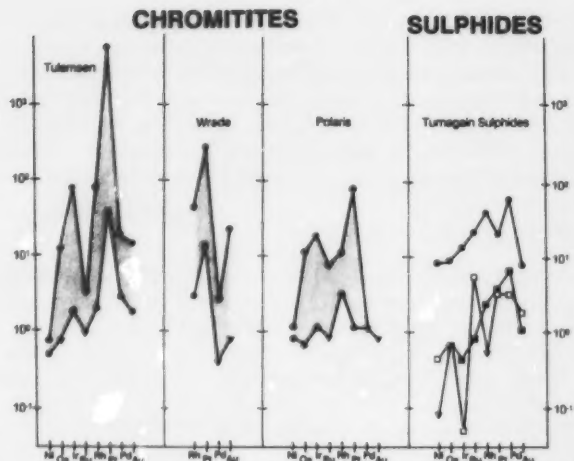


Figure 6-18. Range of normalized noble metal patterns in chromitites and magmatic sulphides of Alaskan-type complexes. Normalizing values and symbols are those used in Figure 6-16 except sulphide symbols which distinguish individual samples.

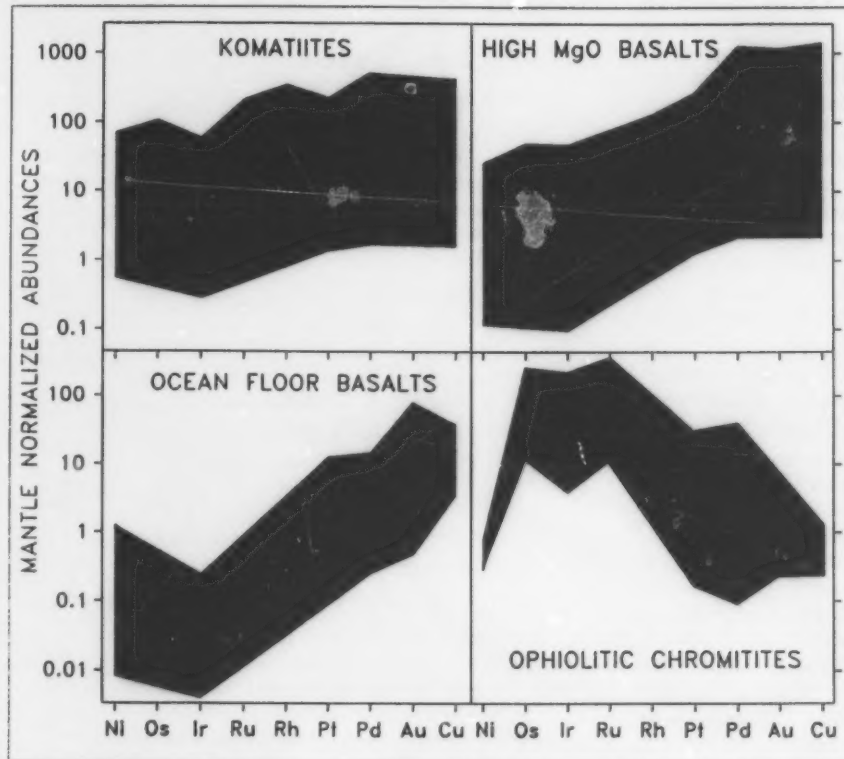


Figure 6-19. Range of mantle-normalized metal patterns for komatiites and the sulphides associated with them; high-MgO basalts and the sulphides associated with them; ocean-floor basalts; and podiform chromitites from ophiolites (after Barnes et al., 1988). Normalizing values are those used in Figure 6-16.

layers are no more than 1 metre in length and 6 centimetres in thickness and are confined to the dunite. They appear particularly abundant on Grasshopper Mountain (Figure 6-15), an area that has been most intensely prospected for PGE. The distribution and structure of these chromitite schlieren have important economic ramifications as detailed below.

PGE OCCURRENCES

Highly anomalous abundances of PGE associated with chromitites in Alaskan-type intrusions have been reported from the Tulameen (St. Louis *et al.*, 1986; Nixon *et al.*, 1990a, Table 1) and Wrede Creek (Hammack *et al.*, 1990) complexes, and other, less pronounced anomalies have also been detected at the Polaris complex (Nixon *et al.*, 1990b).

PGE ABUNDANCES

Some of the highest PGE abundances thus far encountered in outcrop (in chromitites from the Tulameen complex) are given in Table 6-8, and normalized noble metal abundance patterns for rocks from various intrusions are plotted in Figures 6-16 to 6-18 (G.T. Nixon, unpublished data).

A number of general features are evident:

- Chromitites contain the highest absolute abundances of platinum (and iridium) and have high platinum/palladium ratios. This is a typical Alaskan-type feature (Cabri, 1982) and reflects the accumulation of discrete platinum-group minerals (PGM), predominantly platinum-iron alloys, rather than solid solution of PGE in silicates, oxides or sulphides (St. Louis *et al.*, 1986; Nixon *et al.*, 1990a).
- The abundances of PGE are much lower in other rock types, and the abundance of palladium increases with differentiation, reaching a maximum in pyroxenites. This is accompanied by a concomitant decrease of the platinum/palladium ratio.
- Gold is generally uniformly low, although gabbroic rocks at the Johanson and Wrede complexes appear anomalously enriched (Figure 6-17).
- The patterns for magmatic sulphides in the Turnagain complex in northern British Columbia (Figure 6-11) exhibit a fairly smooth enrichment in PGE with a positive slope (one pattern is notably erratic) culminating at Pd (Figure 6-18). The relatively low overall abundances of PGE are somewhat surprising in view of the known affinity of PGE for sulphides and since sulphide immiscibility was reached relatively early in the crystallization history of this intrusion (Clark, 1980). Factors that may explain these PGE-poor sulphides include: 1) the mantle source region was depleted in PGE; 2) a residual PGE-rich phase remained in the source region after partial melting; 3) the silicate magma to sulphide ratio was low; 4) magma chamber dynamics were not appropriate for sulphides to

efficiently scavenge PGE from coexisting silicate melt (Campbell and Naldrett, 1979; Campbell *et al.*, 1983).

- Magnetite horizons in hornblende clinopyroxenites of the Tulameen complex are locally enriched in platinum relative to the other PGE (Figure 6-16). Although it is possible that platinum is contained in magnetite solid solutions, the presence of dispersed PGM is more likely. This unusual geochemical signature is a good example of the subtype 2 association (Table 6-1) and accounts for localized platinum soil anomalies detected by prospectors over hornblende clinopyroxenites at Lodestone Mountain (Figure 6-15).
- The "M-shaped" metal abundance patterns for Alaskan-type complexes, characterized by peaks at platinum and iridium with an intervening trough at ruthenium, are quite unique in comparison to rocks from other geological environments (Figure 6-19 and Barnes *et al.*, 1988, Figure 2). Note that

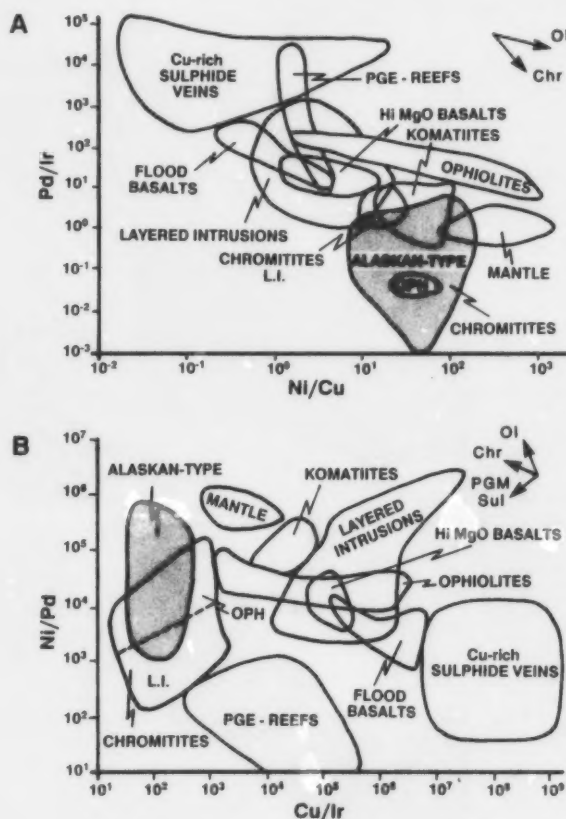


Figure 6-20. A. Pd/Ir versus Ni/Cu and B. Ni/Pd versus Cu/Ir plots for chromitites from Alaskan-type complexes (as represented by the Tulameen complex) and various mafic and ultramafic rock types, Cu-rich sulphide veins and PGE reefs (after Barnes, 1990). Vectors indicate addition of olivine (Ol), chromite (Chr), sulphides (Sul) and platinum-group minerals (PGM).

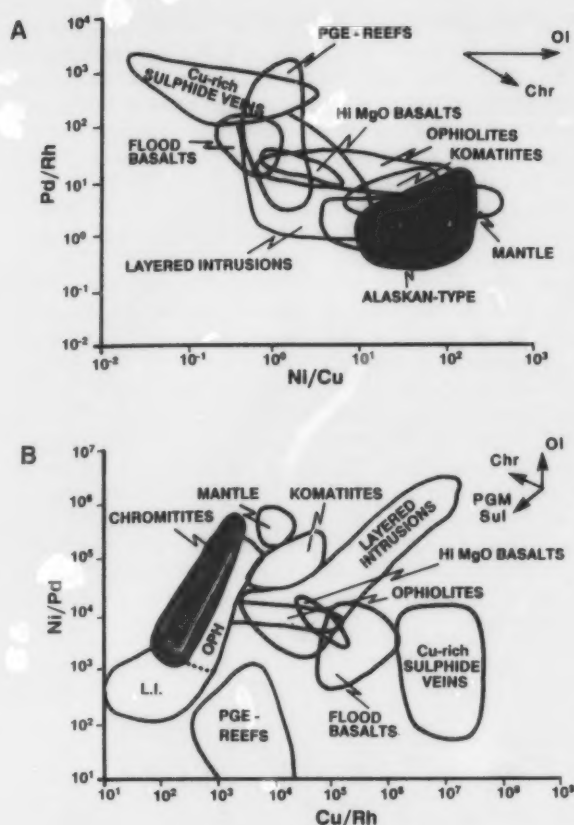


Figure 6-21. A. Pd/Rh versus Ni/Cu and B. Ni/Pd versus Cu/Rh plots for chromitites from Alaskan-type complexes (as represented by the Tulameen complex) and various mafic and ultramafic rock types, Cu-rich sulphide veins and PGE reefs (after Barnes, 1990). Vectors as in Figure 6-20.

sulphide-bearing assemblages have patterns with a positive slope and low platinum:palladium ratios (similar to the sulphide-rich Turnagain complex shown in Figure 6-18), whereas ophiolitic chromitites typically have patterns of opposite slope, which is also the case for British Columbia ophiolites (Whittaker and Watkinson, 1986).

PGE AS AN EXPLORATION TOOL

Recently, Barnes (1990) has shown how the ratios of nickel and copper to PGE may be used to evaluate the potential of mafic and ultramafic rocks for a PGE deposit. Her diagrams are reproduced here (Figures 6-20 to 6-22) and show fields for intrusive and extrusive rocks from various geological environments. Also plotted are chromitites from an Alaskan-type complex (Tulameen) which may be compared to those from layered intrusions (L.I.) and ophiolites

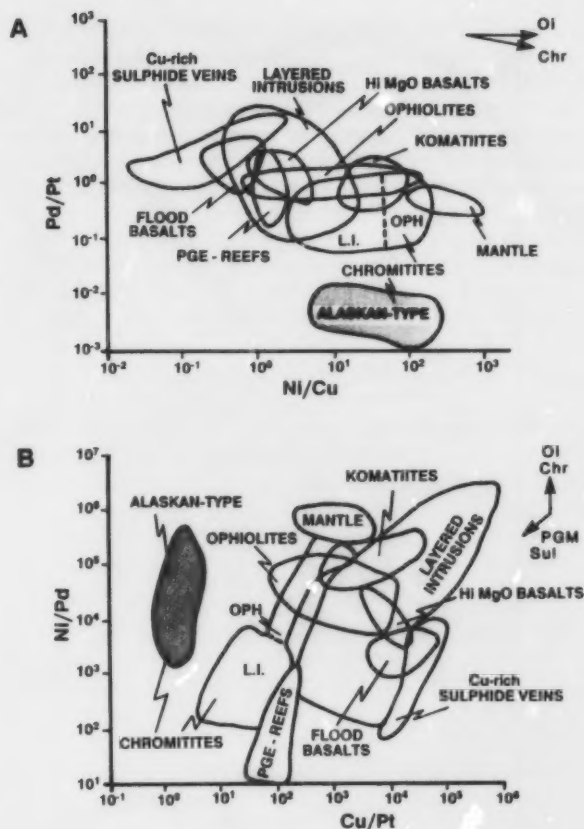


Figure 6-22. A. Pd/Pt versus Ni/Cu and B. Ni/Pd versus Cu/Pt plots for chromitites from Alaskan-type complexes (as represented by the Tulameen complex) and various mafic and ultramafic rock types, Cu-rich sulphide veins and PGE reefs (after Barnes, 1990). Vectors as in Figure 6-20.

(OPH). Figure 6-20 appears to be the most effective discriminant for the various rock types with the notable exception of Alaskan-type chromitites which are best distinguished in Figure 6-22. However, the former diagram is probably less useful for exploration purposes since analysis for iridium is expensive, and commercial laboratories routinely offer cheap analytical packages for platinum, palladium and rhodium. The most important ramification for exploration is that rocks which have nickel/palladium and copper/iridium (or copper/rhodium or copper/platinum) ratios lower than the trend for the extrusive rocks (Figures 6-20B, 6-21B and 6-22B) have experienced some PGE enrichment process and could represent prime exploration targets. Conversely, rocks in which these same ratios are greater than those for the extrusive rocks are depleted in PGE and would be expected to make poor prospecting targets. These conclusions pertain only to magmatic ores and not remobilized or hydrothermal deposits.

Factors affecting the distribution of nickel, copper and PGE in ultramafic and mafic rocks include partial melting and the segregation of olivine, chromite, sulphides and PGM in early crystal cumulates. Progressive partial melting of mantle peridotite yields the trend for mafic extrusive rocks where komatiites represent the highest, and flood basalts the lowest, degree of partial melting. The distinction of various magma types in these plots can be extremely useful (Barnes, 1990). For example, an intrusion might be considered a good target for a PGE deposit if samples from its chilled margin fall within the field of high-MgO basalt since many of the world's most significant PGE deposits (*i.e.*, those hosted by large stratiform complexes such as the Bushveld and Stillwater) are associated with this parental magma type. However, not all PGE-enriched sulphides are associated with the high-MgO magma type; exceptions include the Noril'sk-Talnakh intrusions (Naldrett, 1989) and the recently discovered precious metal-enriched (gold-palladium) zones in the Skaergaard intrusion, Greenland (Bird *et al.*, 1991), although the latter may be subeconomic.

In rocks formed by crystal accumulation, olivine and chromite are the main sources of variation in Figures 6-20A, 6-21A and 6-22A, and drive cumulates toward higher nickel/copper ratios in the direction of the field for mantle peridotite. Thus, if cumulate rocks are the only samples available, the trend for layered intrusions with PGE potential, for example, should project through the high-MgO basalt field. Figures 6-20B, 6-21B and 6-22B may be used to assess the role of sulphides. Because sulphides scavenge the PGE much more efficiently than they concentrate nickel and copper, the segregation of sulphides from a magma causes the nickel/palladium and copper/iridium (or copper/rhodium or copper/platinum) ratios to decrease in the sulphide-bearing cumulate (Barnes, 1990). Thus, a cumulate containing the first-formed sulphides should plot below the trend of extrusive rocks in these plots (*e.g.*, PGE-rich reefs) and consequently point to processes favourable to the formation of a PGE deposit. Note that a second-stage sulphide-forming event in a system closed to renewed magma supply would be expected to yield PGE-poor cumulates.

TABLE 6-9

Platinum-Group Minerals in Tulameen Chromitites and Placers

Mineral	Ideal Formula	Minor Constituents	Chromitites ¹	Placers ¹	Ref. ²
cooperite	PtS	Pd,Ni	—	x	6
Cu-Pt alloy	(Cu,Pt)	Pd,Rh,Fe,Ni,Sb	xx	x	1
erlichmanite	OsS ₂	Pt,Pd,Rh,Ir	x	x	1,6
genkinites	(Pt,Pd) ₄ Sb ₃	Rh,S	x	x	1,4
geversite	PtSb ₂	Rh,Ir,Fe,Cu,Ni,As	xx	x	1,6
hollingworthite- irsarsite series	Rh-Ir(AsS)	Pt,Pd,Rh,Os,Ru,Sb,Cu,Ni,Co	xx	x	1,4,6
iridium	Ir	Pd,Rh,Os,Ru,Fe,Cu,Ni	—	x	5
iridosmine	(Os,Ir)	Pt,Pd,Rh,Ru,Fe,Cu,Ni	—	xx	1,5
isoperplatinum	Pt ₃ Fe	Pd,Rh,Ir,Os,Cu,Ni,Sb	(xxx)	xxx	1,2,6
kotulskite*	PdTe	Pt,Sb,Bi	—	x	6
laurite	RuS ₂	Rh,Ir,Os	x	x	1,6
osmiridium	(Ir,Os)	Pd,Rh,Ru,Fe,Cu,Ni	—	x	1,5
osmium	Os	Pt,Pd,Rh,Ir,Ru,Fe,Cu,Ni	—	xx	5
platiniridium	(Ir,Pt)	Os,Ru,Fe,Cu,Ni	—	x	7
platinum, ferroan	(Pt,Fe)>20 at.% Fe	Ir,Cu,Ni	—	xxx	2,6
platinum, native	(Pt,Fe)>80 at.% Pt	Pd,Ir,Fe,Cu,Ni	x	xxx	2,6
platinum oxide	(Pt,O)?	Rh,Ir,Fe,Cu,Ni,Sb	x	—	1
Pt-Fe-Cu-Ni alloys**	(Pt,Fe,Cu,Ni)	Pd,Rh,Ir,Sb	xxx	x	1
rutheniridosmine	(Ru,Os,Ir)	Pt,Pd,Rh,Fe,Cu,Ni	—	x	5
sperrylite	PtAs ₂	Pd,Ni,Ru,Fe,Sb,S	xx	x	1,4,6
stumpflite	PtSb	Pd,Ru	x	—	4
tetraferroplatinum	PtFe	Pd,Rh,Ir,Cu,Ni,Sb	(xxx)	x	1
tolovskite***	IrSbS	Rh,As	—	x	3,6
tulameenite	Pt ₂ FeCu	Pd,Rh,Ir,Os,Ni,Sb	xx	xx	1,3
unnamed RhSbS	RhSbS	Pt,Ir,As	—	x	3,6

* found as inclusions in one grain of gold; not derived from the Tulameen ultramafic complex.

** see text for nomenclature.

*** Originally reported as unnamed IrSbS (6).

¹ Frequency: xxx=most common; xx=common; x=infrequent to rare; (xxx)=probably present in Pt-Fe-Cu-Ni alloys but not confirmed by XRD.

² References: 1. Nixon *et al.* (1990a); 2. Cabri & Feather (1975); 3. Cabri *et al.* (1973); 4. St. Louis *et al.* (1986); 5. Harris & Cabri (1973); 6. Raicevic & Cabri (1976); 7. Cabri & Hey (1974).

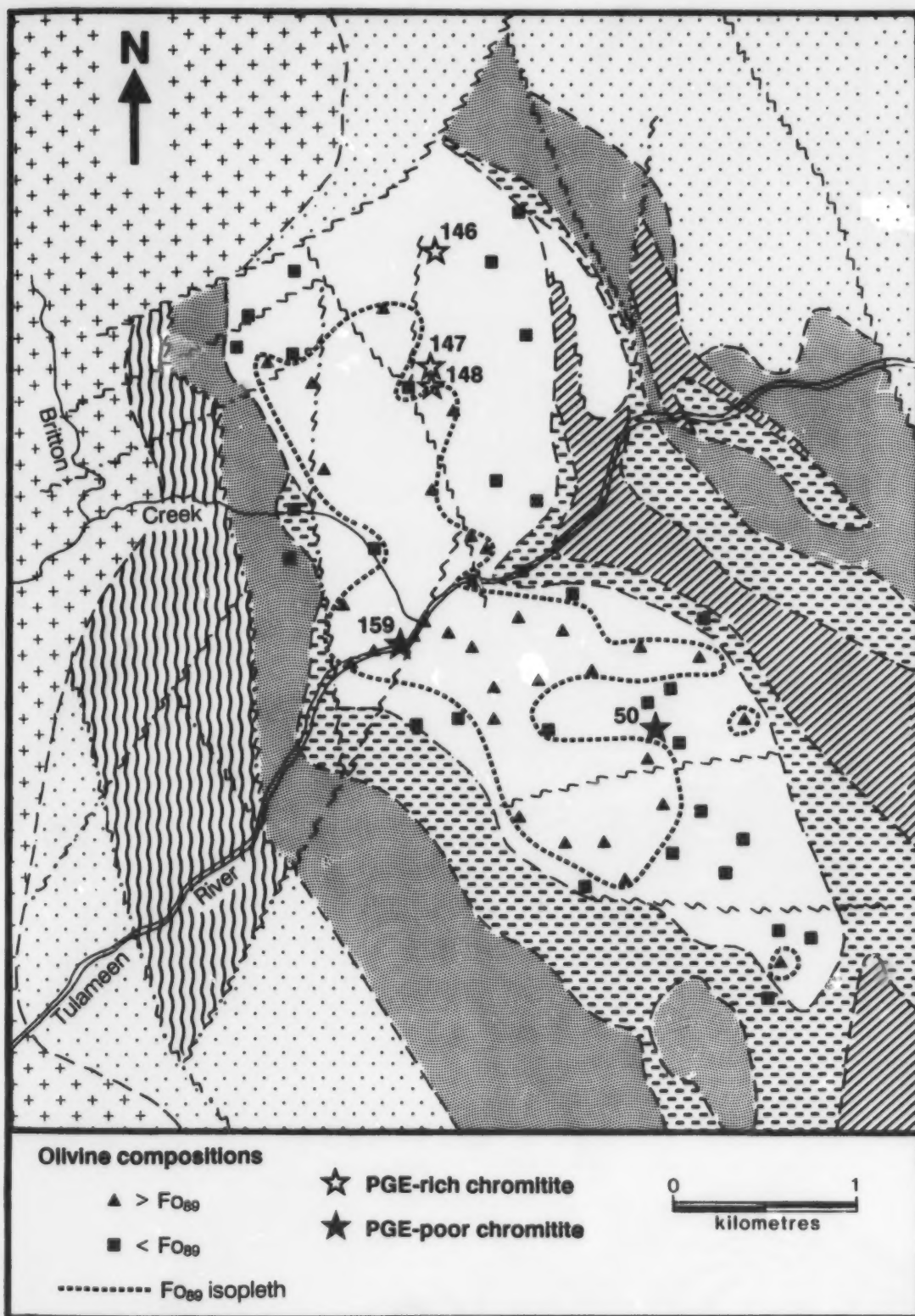


Figure 6-23. Geologic map of the dunite core of the Tulameen complex showing olivine compositions (Findlay, 1963) and chromitite localities (cf. Table 6-8). Other symbols as in Figure 6-15 (after Nixon et al., 1990a).

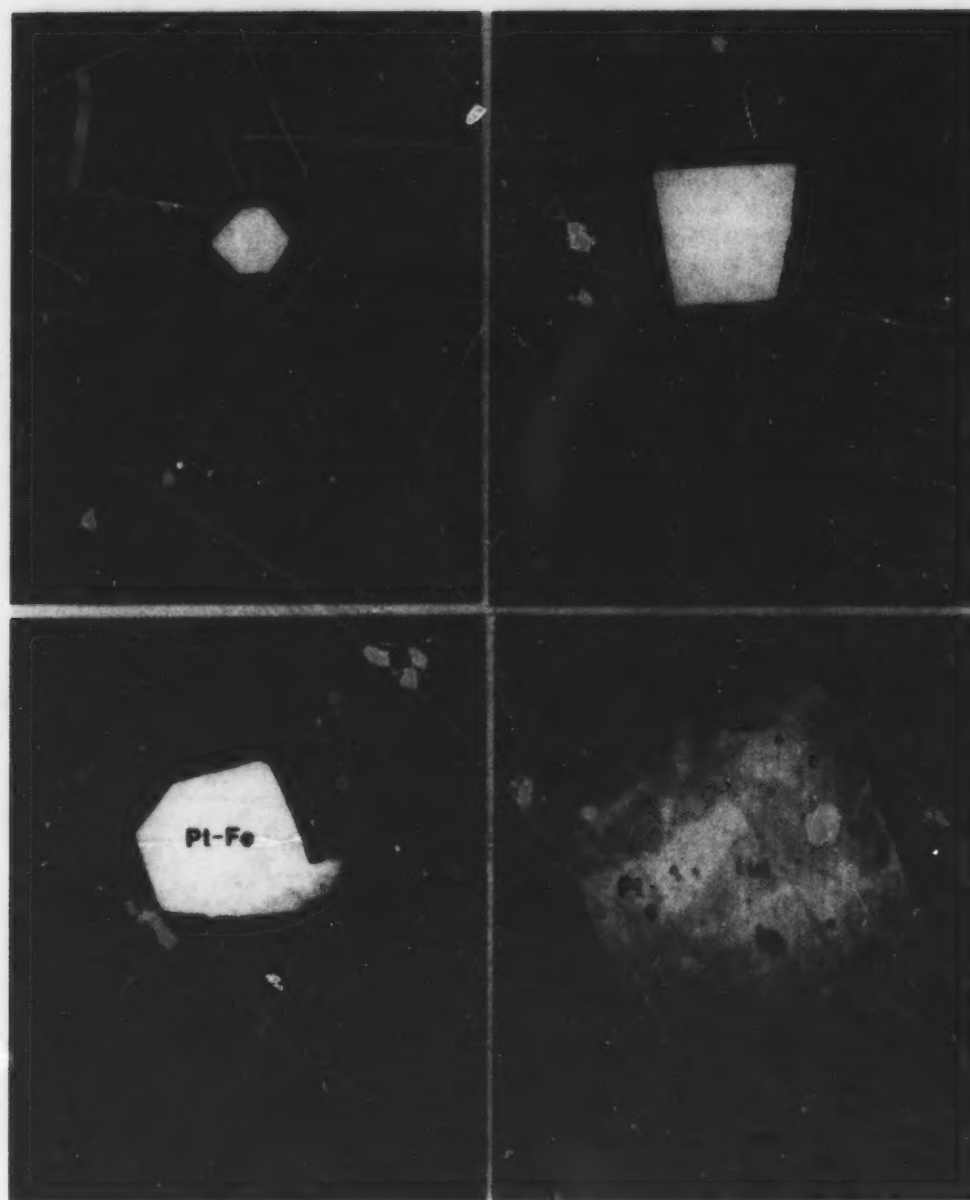


Figure 6-24. Scanning electron-microscope (SEM) photomicrographs of Pt-Fe alloys (Pt-Fe) in Tulameen chromitites. A, B. Euhedral isoferroplatinum(?) inclusions in chromite (cmt); C. Euhedral composite Pt-Fe alloy with peripheral replacement by platinian copper (Cu-Pt) and attached euhedral Mg-rich chlorite (sil); D. Magnification of C showing irregular intergrowth of tulameenite(?) (tul), isoferroplatinum(?) (Pt) and platinian copper (Cu-Pt). Bar scale is 10 micrometres except in D (100 micrometres). (After Nixon et al., 1990a.)

The precipitation of PGM directly from a silicate melt was not specifically addressed by Barnes (1990), but has recently been advanced to account for certain PGE deposits in island arc (Peck and Keays, 1990), ophiolitic (Corrivaux and Laflamme, 1990) and Alaskan-type settings (Nixon *et al.*, 1990a). The distinctive field for chromitites of the Tulameen complex in Figure 6-22 reflects the accumulation of primary platinum-iron-copper-nickel alloys with very low palladium/platinum and copper/platinum ratios that crystallized from sulphur-undersaturated liquids (Nixon *et al.*, 1990a). This diagram therefore appears to be a most effective discriminant for Alaskan-type complexes and may be used to evaluate their PGE potential.

PLATINUM-GROUP MINERALS (PGM) AS AN EXPLORATION TOOL: LODGE VERSUS PLACER DEPOSITS - THE CHROMITITE CONNECTION

Placers in the Tulameen and Similkameen River systems have been important past producers of

PGE, having yielded some 620 000 grams of platinum between 1889 and 1936. The source of the placer mineralization has traditionally been assumed to be the ultramafic rocks of the Tulameen complex. New data incorporated here confirm this hypothesis and forge a strong link between placer nuggets and chromitite horizons in the core of the complex (Figure 6-23).

The mineralogy and relative abundance of PGM in lode and placer occurrences in the Tulameen region is summarized in Table 6-9 (Nixon *et al.*, 1990a). The most common PGM in lode and placer occurrences are platinum-iron alloys (notably tetraferroplatinum and isoferroplatinum) and tulameenite. Notable differences include the predominance of isoferroplatinum in placers versus tetraferroplatinum in chromitites, and the higher frequency of geversite, sperrylite and rhodium-iridium sulpharsenides in the latter. Marked contrasts also exist in their textural attributes: isoferroplatinum in placer nuggets forms millimetre-scale grains that enclose large crystals

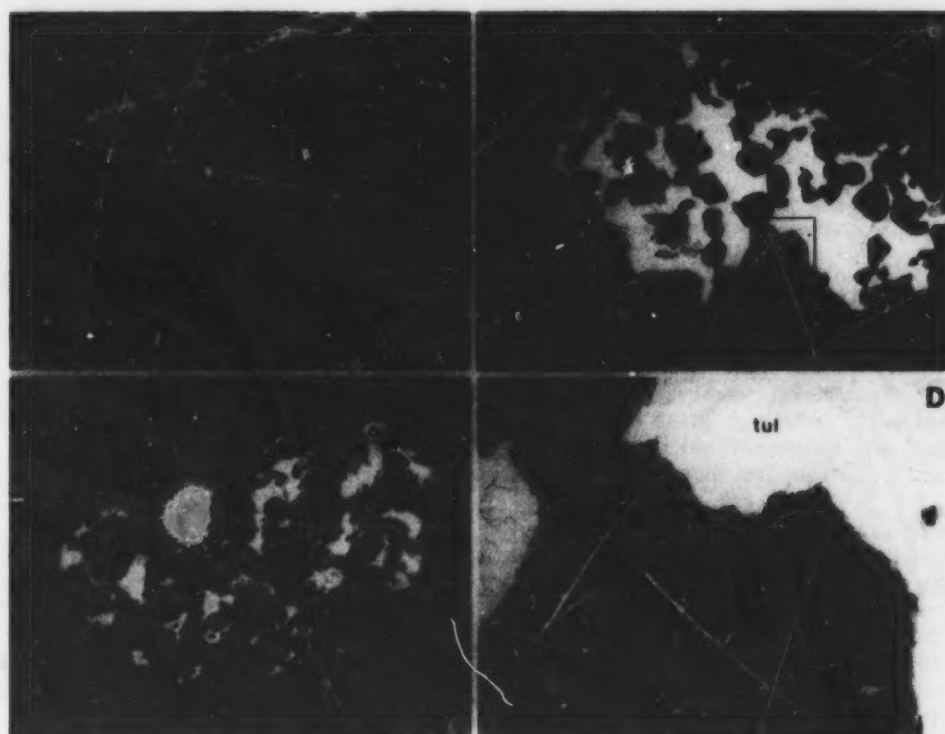


Figure 6-25. SEM photomicrographs of a platinum nugget recovered from the Tulameen River near the junction with Lawless Creek (Figure 6-15). A. Low-magnification image of irregular surface features of the nugget; B. Backscattered electron image clearly distinguishing chromite (dark grey) from platinum alloy (white) comprised mainly of tulameenite, minor isoferroplatinum(?) and rare tetraferroplatinum(?); C. cross-section of nugget showing subhedral chromite (cmt) set in a matrix of platinum alloy; D. Enlargement of area outlined in C showing chromite and olivine (oll) in contact with tulameenite (tul), which is veined and rimmed by platinian copper (light grey). Bar scale is 1 millimetre except in D (100 micrometres). (After Nixon *et al.*, 1990a.)

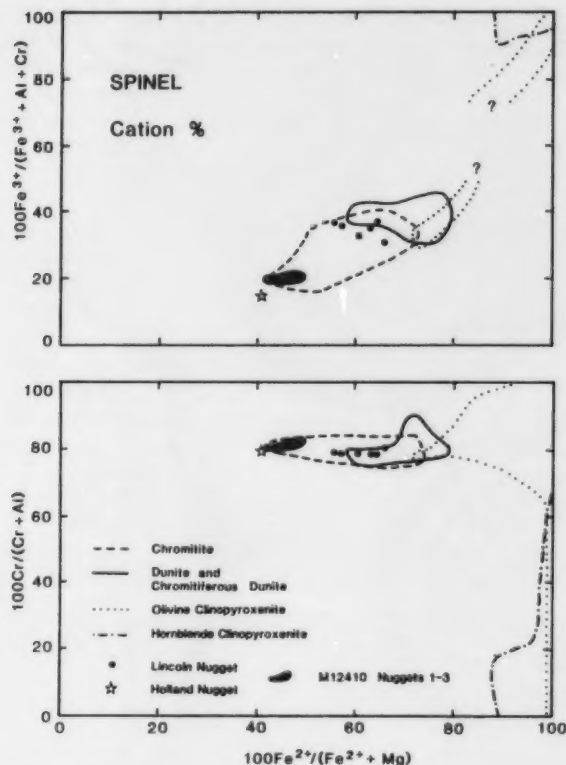


Figure 6-26. Plot of the compositions of chromite in placer nuggets (32 analyses) versus spinels in Tulameen rock types (264 analyses) (after Nixon et al., 1990a).

of chromite and olivine; tetraferroplatinum in chromitites forms minute euhedral crystals (<30 micrometres in diameter) locked in chromite (Figures 6-24 and 6-25). Although these textures are clearly primary and magmatic, such contrasts in mineralogy and texture suggest different sources for the PGM.

The composition of gangue minerals in PGE nuggets, chiefly olivine and chromite, has an important bearing on the characteristics of the placer source. Chromite compositions in selected PGE-rich nuggets are compared to those in Tulameen chromitites in Figure 6-26. Most nugget spinels fall within the field of Tulameen chromitites, although one exhibits some overlap with spinels in dunite. The gap in spinel compositions for olivine clinopyroxenites appears real, and is related to a sharp decrease in the modal abundance of chrome spinel in pyroxenites. From these data, it is clear that the abundance and composition of chromite in these nuggets points to the derivation of PGE-enriched placer materials from the dunite core of the Tulameen complex.

Analyses of olivines in nuggets and ultramafic rocks are plotted in Figure 6-27. Nugget olivines have compositions significantly removed from those

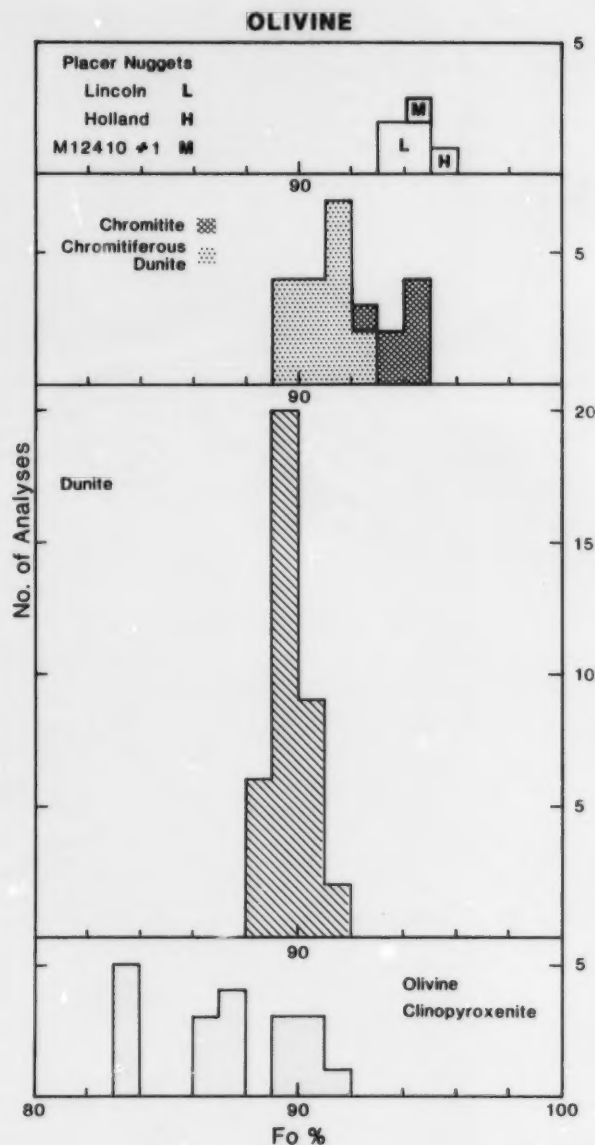


Figure 6-27. Histogram showing the distribution of olivine compositions (mole per cent forsterite) in placer nuggets (8 analyses) and ultramafic rocks (80 analyses) of the Tulameen complex (after Nixon et al., 1990a).

in olivine clinopyroxenites and dunites, but match rather closely the olivines in chromitites. From the extensive areal sampling and analysis of olivines conducted by Findlay (1963), it is possible to conclude that olivine analyses in the dunite are indeed representative of the mass as a whole (Figure 6-23). The much more magnesian nature of the chromitite olivines is explained by high-temperature subsolidus exchange of iron and magnesium between chromite and olivine during cooling of a chromite-dominant

hostrock (e.g., Irvine, 1965; Clark, 1978). These data, therefore, point rather conclusively to a chromitite source for the PGE mineralization in the placers. The exact chromitite horizon that hosted our nuggets either has eluded sampling or has been removed by erosion. Regardless, the use of gangue mineral compositions to deduce the provenance of placer mineralization has a great deal of potential in mineral exploration.

IMPLICATIONS OF PGM SPECIATION AND PGE ABUNDANCES FOR EXPLORATION

The mineralogy and relative abundances of PGE in Alaskan-type intrusions have important implications for geochemical prospecting. The fact that PGE in Alaskan-type complexes are concentrated predominantly in relatively inert alloys suggests that PGE signatures are likely to be fairly robust during weathering and transportation.

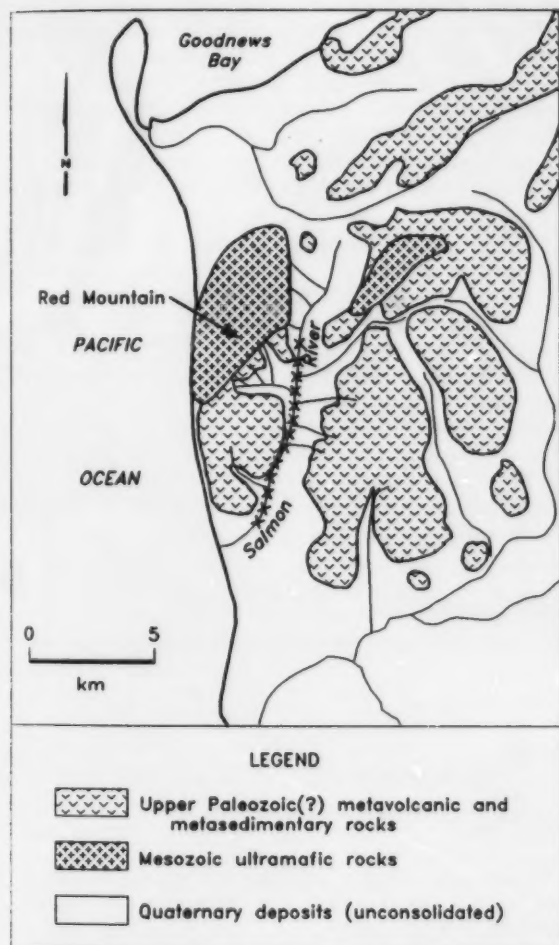


Figure 6-28. Generalized geology of the Alaskan-type ultramafic complex near Goodnews Bay, Alaska (simplified from Mertie, 1976). X, sample localities for PGE data plotted in Figure 6-29.

The Goodnews Bay mining district in Alaska (Mertie, 1976) provides an excellent example of the robust nature of PGE alloys. Here, high-grade platinum placers have been worked since 1927 in the valleys of the Salmon River and its western tributaries which drain the eastern slopes of an Alaskan-type intrusion at Red Mountain (Figure 6-28). The source of the platinum has been traced directly to this intrusion which is composed largely of dunite. The PGE are contained in two principal alloys: relatively coarse-grained platinum-iron alloy accompanied by minor, finely crystalline (<30 micrometres) laths and blades of osmiridium (Mertie, 1976; Rosenblum *et al.*, 1986). These alloys are commonly intergrown with fine-grained magnetite in the smaller grains, or chromite in the larger nuggets.

PGE analyses of placer concentrates representing dredge cleanups of pay streaks along the floor of the Salmon River (Mertie, 1976) are plotted in Figure 6-29. Without exception, PGE abundances are dominated by platinum with minor iridium and osmium, and reflect the composition of the major alloys. The PGE exhibit the same distinctive M-shaped abundance pattern that characterizes Tulameen chromitites (Figure 6-18) and other Alaskan-type complexes. In detail, there is a systematic increase in the abundance of osmium and iridium downstream, accompanied by a decrease in platinum. This may be explained by an increase in the proportion of fines (<100 mesh), and hence iridosmine, downstream coupled with an influx of iridosmine-rich material from creeks entering the lower reaches of the Salmon River (Mertie, 1976). Despite these com-

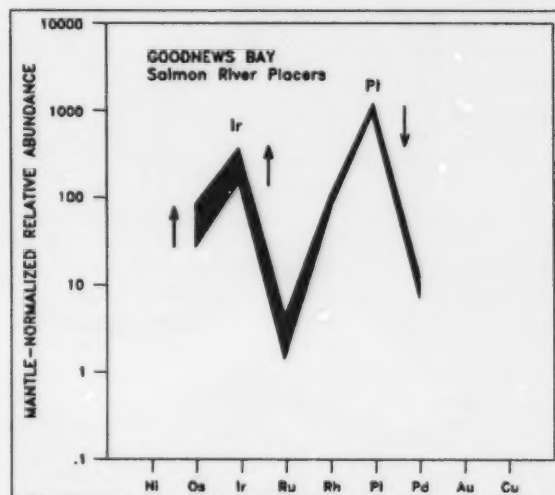


Figure 6-29. Range of mantle-normalized relative abundances of PGE in concentrates from dredge cleanups along the Salmon River, near Goodnews Bay, Alaska (Mertie, 1976, Table 22). Arrows indicate systematic changes in abundance of Pt, Ir and Os with distance downstream. Normalizing values are those used in Figure 6-16.

plexities, the PGE pattern does not change and uniquely identifies an Alaskan-type source. These observations should encourage the analysis of panned concentrates when prospecting for the lode source of PGE in placers.

GOLD

The distribution and genesis of gold deposits in the Cordillera are treated more thoroughly by Panteleyev (this volume). However, throughout the Cordillera as a whole, there is an intimate *spatial* relationship between some gold deposits and ultramafic complexes of ophiolitic affinity. The brief discussion below centres on these affinities and highlights the listwanite (carbonatized ultramafic rock)-lode gold association and spatially-related gold-bearing placers (Table 6-1). Examples in British Columbia are largely abstracted from recent work by Ash and Arksey (1990a, b, c).

LISTWANITE MODEL

The listwanite model described here is that of Buisson and Leblanc (1986). Listwanite-associated lode gold and related placer deposits are tectonically linked with the ophiolite suite. This structurally complex environment facilitates access of hydrothermal fluids to serpentinized ultramafic rocks (Figure 6-30). Listwanitic alteration is preferentially developed along fault zones, and spatially related

quartz veins commonly occupy dilatant fractures that may be arranged en echelon. The alteration is generally considered to occur during the late stages of emplacement of the serpentinized ultramafic bodies, but it would be unwise to consider all such alteration to be syn-emplacement.

Listwanitic lenses along fault zones usually grade into surrounding serpentinite through a talc-carbonate zone, reflecting addition of carbon dioxide and calcium, and loss of silica and magnesium. The listwanites are light grey rocks with distinctive orange-brown recessive weathering. Mineralogically, they comprise magnesium-iron-calcium carbonates with quartz, talc, chlorite, hematite, magnetite, and pyrite. A bright green, chrome-rich mica (mariposite/fuchsite), formed from the alteration of chrome spinel, is a locally distinctive constituent. These minerals are commonly associated with a variety of base and precious metal sulphides, arsenides and tellurides. In this respect, the listwanite model is identical to that proposed recently for the genesis of gold-bearing and PGE-bearing cobalt-arsenide ores in serpentinized ophiolites (Leblanc and Fischer, 1990; and see also the Limassol Forest cobalt-nickel ore deposit model of Cox and Singer, 1986, 8c). Native gold may accompany these sulphides or occur in quartz veins. The history of quartz veining in any single deposit may be rather complex.

The genesis of listwanites involves carbon dioxide-calcium metasomatism of serpentinized peridotites by mesothermal (150–300°C) fluids, a process illustrated schematically in Figure 6-31. The fluids originate from a variety of sources and the origin of the gold is widely disputed. Gold values in the listwanites have been found to range from 0.02 to 1 ppm, whereas serpentinized wallrocks may contain only 5 to 10 ppb gold (Buisson and Leblanc, 1986). A list of potential geochemical pathfinder elements in areas affected by listwanitic alteration is given in Table 6-10.

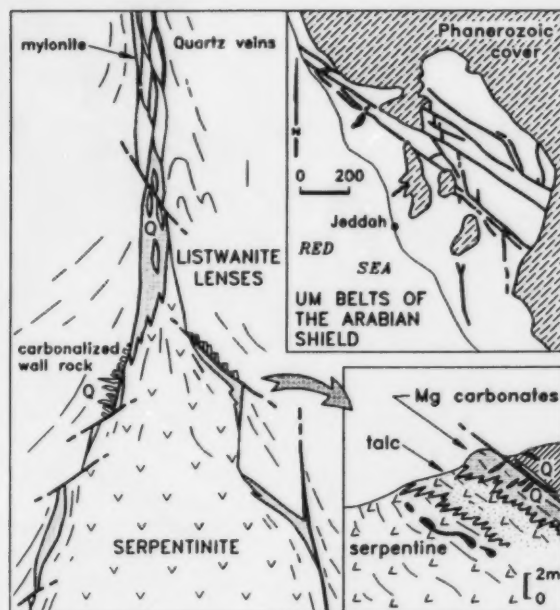


Figure 6-30. Schematic cross-section of listwanite development in serpentinized Alpine-type peridotite, Saudi Arabia (after Buisson and Leblanc, 1986).

TABLE 6-10

Potential Pathfinder Elements for Gold in Listwanite

Location	Strong Positive Correlation With Au	Positive and Sporadic Correlation With Au	Source
Atlin, B.C.			
Yellowjacket	As, Sb	Ag, K	
Pictou	As, Sb	Ag, Cd, Cu, Pb, Zn	Bozek (1989)
Cassiar, B.C.			
Erickson	As, Ba, K, B	Ag, Cu, Pb, Zn, Sb	Sketchley (1986)
Washington State			
Mount Vernon	Li	K, Na, Zn, Pb	Gresens et al. (1982)
European ophiolites	As, K	Sb, Ba, B, Bi, Ag, Cu	Buisson and Leblanc (1986)

(after Ash and Arksey, 1990a)

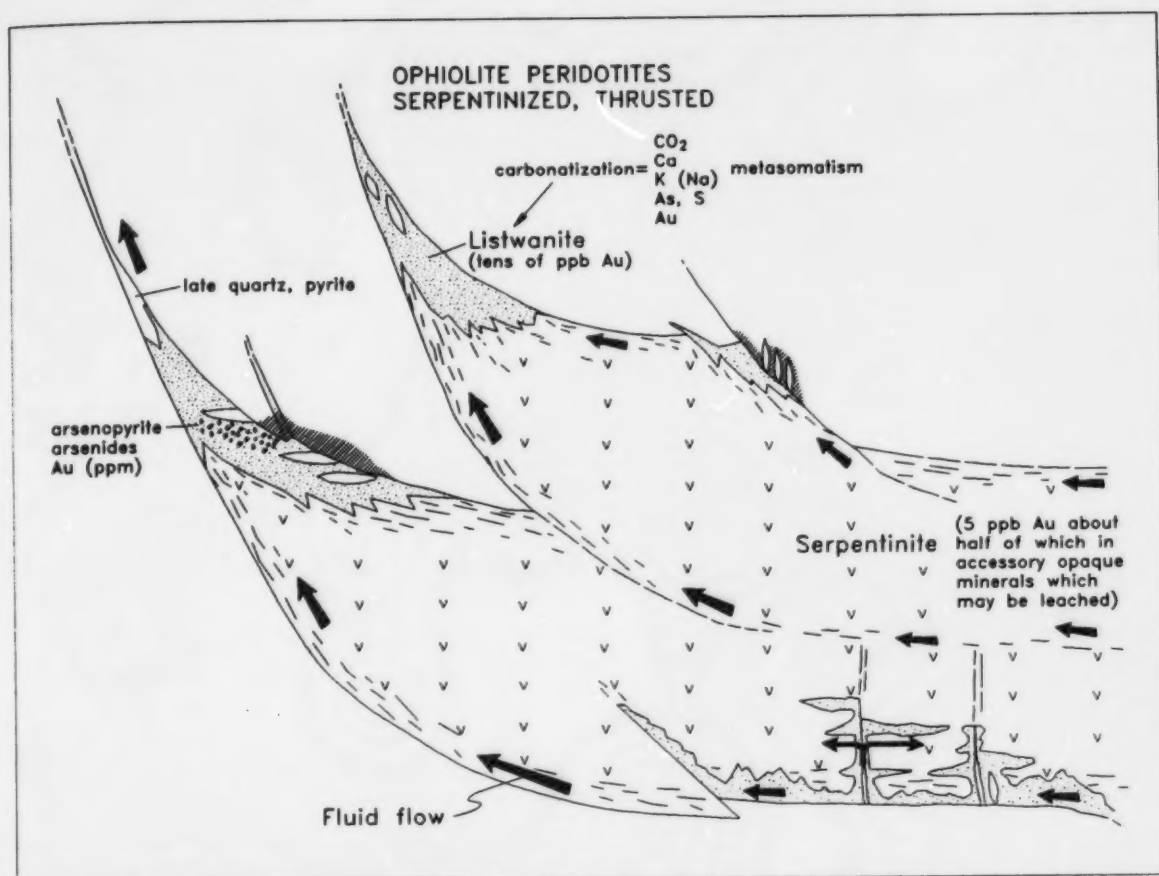


Figure 6-31. Genetic model for gold-bearing listwanites (after Buisson and Leblanc, 1986).

LISTWANITE OCCURRENCES

Listwanite-associated lode gold occurrences in British Columbia are found in the accreted oceanic assemblages of the Intermontane Belt (Figure 6-11) and appear in some of the major gold camps, including Bridge River, Atlin and Greenwood. The relationships between tectonic setting and listwanite-associated lode gold occurrences may be illustrated by reference to recent work by Ash and Arksey (1990b) in the Atlin camp.

The Atlin-Monarch Mountain area is underlain by serpentinitized mantle peridotites that form part of an allochthonous ophiolite sequence emplaced along the Monarch Mountain thrust. Well-developed listwanitic alteration accompanied by quartz veins is everywhere localized along faults and even affects tectonic mélangé units. Some of the major auriferous placer streams such as Pine and Spruce creeks (over 19 million grams of gold recovered since 1898 in the Atlin area) have excavated channels into listwanite-altered bedrock.

Lode gold occurrences in the Atlin region are spatially associated with listwanitic alteration along faults. The Pictou property, for example, is located on the trace of a carbonatized fault in serpentinitized harzburgite. A wide variety of base metal sulphides have been detected, including galena, chalcopyrite, sphalerite, arsenopyrite, pyrrargyrite and gersdorffite (Ash and Arksey, 1990b). Assays of bulk samples of the mineralized zone have yielded up to 342 grams per tonne gold, 0.33 weight per cent lead and 0.16 weight per cent zinc. In addition, gold assays as high as 13.5 grams per tonne have been obtained from sulphide-bearing quartz veins. Similar veins further south at the Erikson mine (Figure 6-11) have yielded maximum PGE abundances of 1090 ppb platinum and 230 ppb palladium (C. Ash, personal communication, 1991). Other prospects in the Atlin area associated with fault-controlled listwanitic alteration include Yellowjacket, Beavis, Golden View and Lakeview (Bloodgood *et al.*, 1989), and a general model for listwanite-associated lode gold occurrences in this region is given in Figure 6-32 (Ash and

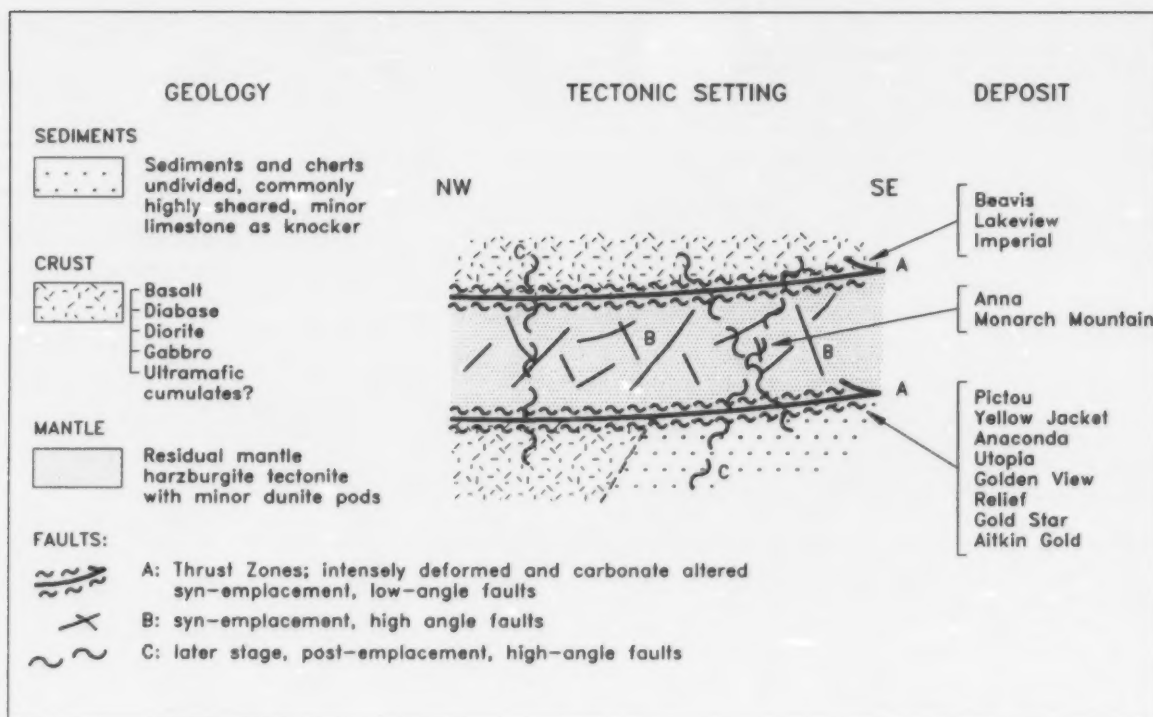


Figure 6-32. Lithotectonic setting of listwanite-lode gold deposits near Atlin, northern British Columbia (after Ash and Arksey, 1990c).

Arksey, 1990c). Perhaps the most important aspect of the listwanite model for lode gold occurrences is that it provides a basis for developing a rational strategy for gold exploration in ophiolitic terranes.

ACKNOWLEDGMENTS

This paper is an outgrowth of work conducted under the Mineral Development Agreement between Canada and the Province of British Columbia (1985-1990). We extend our appreciation to S.-J. Barnes, C. Bow and M.L. Zientek for reviewing the manuscript; C. Ash for allowing us to quote unpublished data; and B. Grant and J.M. Newell for editorial handling. Any errors that remain are truly ours!

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GOLD IN THE CANADIAN CORDILLERA — A FOCUS ON EPITHERMAL AND DEEPER ENVIRONMENTS

by Andrejs Panteleyev

INTRODUCTION

GOLD PRODUCTION

Gold is historically the most important metal and second commodity after coal to be mined in the Canadian Cordillera. Lode gold was first mined in 1852 from quartz veins in the Queen Charlotte Islands; placer gold was first won by miners of European extraction in 1857 from diggings on a tributary of the Thompson River near the present site of Lytton. Aboriginal people had presented placer gold to traders a few years earlier.

Total Canadian Cordilleran gold production recorded to 1990 is 1251 tonnes: 708 tonnes from lode sources mainly in British Columbia, the rest from placer workings. Reported placer output totalling 378 tonnes from Yukon and 165 tonnes from British Columbia is dominated by production in the late 1890s from the Klondike gold fields of the Yukon, and during the mid to late 1800s from the Cariboo gold fields of central British Columbia. The Yukon gold deposits were among the richest placer fields in the world, mainly because they escaped dispersal by glaciation. The concentration of gold might also have been due to changes in base level leading to repetitive peneplanation as well as an unknown amount of gold redeposition in the supergene environment (Henley and Adams, 1979). Placer and lode gold sources are commonly spatially associated and many lode deposits have been discovered as a consequence of exploration for 'motherlode' sources in or near placer areas.

More than 100 significant mines in British Columbia have produced lode gold since 1894 as a primary or significant byproduct commodity but nearly 60 per cent of the gold produced has come from six major camps, each providing in excess of 31 tonnes gold (over 1 million ounces). These are: Bridge River, Rossland, Portland Canal-Stewart (Premier), Hedley, Cariboo-Barkerville and Boundary-Greenwood. The major primary producers, Bridge River, Rossland, Cariboo-Barkerville, as well as Sheep Creek-Ymir, are structurally and, in part, stratigraphically controlled mesothermal quartz veins and pyritic replacement deposits or cupriferous gold veins. Hedley is a skarn gold deposit (see discussion by Ray, this volume). The Portland Canal-Stewart deposits, including the major gold-silver producer, Premier mine and the newly discovered Iskut area deposits to the northwest, are subvolcanic or epizonal pluton-related vein and stockwork deposits.

Sources of gold in the Greenwood-Boundary camp are skarn copper and copper-magnetite deposits and their related peripheral veins. Other major byproduct gold has come from the Island Copper porphyry copper-molybdenum mine, Copper Mountain-Similkameen (Similco) and Bell porphyry copper deposits and the Myra Falls (Westmin) and Britannia volcanogenic massive sulphide deposits. The eleven major producers are listed in Table 7-1.

Cordilleran gold production in 1990 was about 21 tonnes, about 13 per cent of total Canadian output. British Columbia produced 16.44 tonnes from lode deposits, Yukon produced 4.6 tonnes with 75 per cent coming from placer deposits. Peak historic lode gold production in British Columbia was in 1939 when 18.3 tonnes was produced from 188 deposits. The smallest gold production was in 1971 when 2.7 tonnes gold was recovered, virtually all as a byproduct of base metal mining. At the beginning of the 1980s, approximately 80 per cent of gold production was a byproduct of porphyry copper, massive sulphide and iron-copper skarn deposits. The price increase for gold in 1979 regenerated mining of primary precious metal ores. During the 1980s primary gold production from new mesothermal and epithermal vein and related discoveries increased markedly and currently accounts for about 50 per cent of annual Cordilleran gold output.

British Columbia gold production in 1991 is estimated to be close to 18 tonnes (578 700 ounces). New gold-silver mines opened in 1989 include: Premier Gold, Cheni (Lawyers), Shasta, Golden Bear and Samatosum; Snip and Silver Butte began production in 1991. Lode gold reserves in British Columbia are estimated to be over 1350 tonnes (Schroeter *et al.*, 1989), about double all previous production. Porphyry copper deposits contain more than half of this total and veins contain about one third. For a detailed review of gold production and reserves in British Columbia see Schroeter *et al.* (1989) and Schroeter and Lane (1991). Yukon gold deposits are listed in Morin and Downing (1984). A summary of the geology and deposit descriptions of major Canadian Cordilleran mines and districts is provided by Barr (1980).

DEPOSIT CLASSIFICATION

Gold deposits are commonly assigned to two fundamental categories — mesothermal and epithermal (see Tables 7-2 and 7-3). The terms refer to depth zoning of mineralization and were used by Waldemar

TABLE 7-1

Major Lode Gold Producers (to end 1989)

NAME	PRODUCTION Years	TONNES Milled to end 1989	GOLD Recovered kg	GOLD Reserves kg	SILVER Recovered kg	DEPOSIT TYPE
1. BRIDGE RIVER CAMP: Bralorne, Pioneer, Congress, Wayside, Reliance, Minto	1899-1978	7 317 300	129 953	17 617	31 180	Mesothermal quartz veins
2. ROSSLAND CAMP: Le Roi, Centre Star, Josie, War Eagle, etc.	1894-1974	5 623 200	85 387		107 020	Mesothermal sulphide veins
3. PREMIER includes Premier Gold starting 1989	1918-1976, 1989	4 618 740	56 163	9 230	1 274 691	Epithermal quartz stockworks
4. HEDLEY CAMP: Nickel Plate, Hedley Mascot, French, Good Hope, etc.	1904-1961, 1982, 1983, 1987-	4 020 000	52 194	31 294	6 827	Gold skarn
5. CARIBOO-BARKERVILLE CAMP: Cariboo Gold Quartz, Island Mountain (Aurum), Mosquito Creek	1933-1987	2 746 300	38 295	1 525	5 144	Mesothermal quartz veins and sulphide replacements
6. GREENWOOD CAMP: Phoenix, Motherlode, BC, Greyhound, Emma, Oro Denoro, etc.	1900-1978	28 875 900	37 058	3 611	224 551	Copper - magnetite skarn
7. ISLAND COPPER	1971-1989-	219 811 000	24 790	7 620	181 061	Porphyry
8. SHEEP CREEK CAMP: Queen, Reno, Kootenay Belle, Gold Belt, Nugget, Vancouver	1902-1981	1 531 900	23 685	2 302	9 117	Mesothermal quartz veins
9. SIMILKAMEEN (Similco): Copper Mountain, Ingerbelle, Virginia, Alabama	1917-1962 1972-1989-	143 872 000	19 385	14 961	251 847	Porphyry
10. LYNX, MYRA, H-W, Price (Westmin)	1966-1989-	10 400 845	17 105	22 044	714 829	Massive sulphide
11. BRITANNIA	1905-1977	47 875 100	15 336		180 879	Massive sulphide

Lindgren as early as 1911 and first published in 1922. Lindgren and a number of predecessors articulated that depth-dependent pressure and temperature conditions determine mineralization styles in virtually all types of rocks. Lindgren formalized his depth classification in his 1933 book *Mineral Deposits*, page 212, Fourth Edition. His genetically based classification describes mineralization that we now term 'epigenetic' as:

" Origin dependent upon the eruption of igneous rocks. By hot ascending waters of uncertain origin, but charged with igneous emanations.

1. **Epithermal deposits.**

Deposition and concentration at slight depth. Temperature, 50-200°C±. Pressure, moderate.

2. **Mesothermal deposits.**

Deposition and concentration at intermediate depths. Temperature, 200-300°C±. Pressure, high.

3. **Hypothermal deposits.**

Deposition and concentration at great depth or at high temperature and pressure. Temperature, 300-500°C±. Pressure, very high."

Lindgren's classification was quickly recognized to be inadequate and soon embellished. Graton (1933) placed depth limits of 6000 feet (1.8 km) for epithermal, 20 000 feet (6 km) for mesothermal and 50 000 feet (15 km) for hypothermal. He also defined two new terms: **Leptothermal** — between meso and epithermal, commonly referred to as 'telescoped' deposits with both high and low temperature attributes, and **Telethermal** — shallow depth, epithermal-type cool fluids but far-travelled without any demonstrable igneous source. A third term was introduced by Buddington (1935): **Xenothermal** — shallow depth and low pressure but far too hot to be 'epithermal', for example, some high level tungsten deposits. Despite its evident deficiencies, the Lindgren genetic classification is still extensively used, especially in the English-speaking world.

TABLE 7-2

Characteristics of Cordilleran Mesothermal and Epithermal Gold Deposits

	MESOTHERMAL	EPITHERMAL
Tectonic setting	Crustal scale high strain zones. Convergent and transpressional continental margins; accretionary clastic wedge, oceanic allochthons; deformed greenstone belts	Extensional, transtensional. Terrestrial volcanic fields, stratovolcanos; volcano-plutonic arcs and back-arcs, volcanic island arcs
Structural setting	In brittle-ductile transition zones. Regional crustal breaks: terrane-bounding faults, strike-slip faults, major fault/shear zones Deposit: steep normal or reverse faults in deformation zones, secondary faults and splays off major faults, shear zones, fold hinges	Regional: grabens, volcanic structures — caldera, maar, flow-dome complex; intrusive centres with subvolcanic stocks and dikes Deposit: faults, breccia, tensional openings, cymoids; fossil geothermal fields and hot springs
Associated rocks	Wide variety — mafic to felsic volcanics, plutons, clastic sediments (commonly graphitic), serpentinite, limestone	Subaerial intermediate to felsic volcanic flows and pyroclastic rocks, subvolcanic plutons and dikes, diatremes, hot spring deposits
Metamorphism	Sub to upper-greenschist facies, commonly retrograde from higher grade metamorphic rocks	Unmetamorphosed or shallow burial zeolite facies
Mineralogy, ore	Pyrite, pyrrhotite, arsenopyrite, bismuthopyrite, sphalerite, galena, native Au, scheelite, bismuthinite, tetrahedrite, stibnite, Au and Ag tellurides	Pyrite, electrum, native Au and Ag, argentite/acanthite, sphalerite, galena, chalcocopyrite, silver sulphosalts, tetrahedrite/tennantite, selenides, enargite; locally cinnabar, stibnite, sulphur & native arsenic
Au/Ag ratio	1 to 10	Less than 1, typically 1/5 to 1/20 in gold and gold-silver deposits. Variable in silver-rich deposits.
Characteristic elements associated with gold	Ag, As, Bi, W, Sb, Te, B with variable, commonly minor, Mo, Cu, Pb, Zn, Hg	Ag, As, Hg, Sb, Te, Se, Mn, W
Gangue	Quartz, Ca-Fe-Mg carbonate, albite, muscovite, mariposite, graphite, talc, chlorite, tourmaline	Quartz, amethystine quartz, chalcedony, calcite, adularia, barite, fluorite, rhodochrosite, rhodonite, sericite, clays (illite/smectite $\pm$ kaolinite), chlorite; kaolinite, alunite $\pm$ pyrophyllite
Vein textures	Large veins: coarsely crystalline white 'bull or buck' quartz in euhedral and anhedral intergrowths, ribboned, superimposed stylolites, 'spider' veinlets and fractures, complex banding, commonly graphitic, rarely vuggy; locally stockworks with anastomosing gashes and dilations. Less commonly cupriferous base metal sulphide intergrowths.	Veins and stockworks; open-space filling, vuggy, comb textures, crustified, colloform, banded, microcrystalline with cockade overgrowths; multiple generation breccias and much silica overprinting; disseminations
Hydrothermal alteration	Carbonate (ankeritic), albite, potassic, sericite, chlorite, 'Listwanite' (quartz, ankeritic carbonate, mariposite, talc), pyrite (sulphidation). Forms wallrock alteration envelopes. Age related to structures or nearby intrusions.	Dominantly silicification; K-feldspar, propylitic, sericitic, argillic, advanced argillic. Age closely related to age of host rocks
Fluid circulation	Deep circulation, tectonically or seismically driven, subsequent to principal deformation and metamorphism. Alkaline to near-neutral pH, reduced, highly evolved with extensive isotopic exchange with wallrocks; depth — 10 to 15 km, mineralization commonly around 10 km, vertically extensive, relatively uniform with some variation in pyrite:pyrrhotite, carbonate compositions and minor element contents, for example Hg and Sb	Shallow magmatically driven upflow with more extensive gravity driven outflow. Meteoric source dominant, alkaline chloride neutral pH to oxygenated, strongly acidic; depth <3 km, mineralization commonly less than 1.5 km, vertically restricted with marked vertical zoning
Fluid Inclusion data	200–400° C, typically 250–350 °C	<200–300° C
Temperature (T_{homog})	intermediate to high, >4 mol %, normally 10–25 mol % CO ₂	Low to intermediate, <4 mol % CO ₂
CO ₂ content	Low — 0 to 5 wt %, typically <2 wt % NaCl equivalent	Low — 0 to 4 wt % normally, to 13 wt % in base metal-bearing deposits and up to 24 wt % NaCl equivalent in highly sulphidized, advanced argillic zones
Salinity		
Pressure	>100 000 kPa (>1 kb), normally 1–3 kb CO ₂ + H ₂ O phase separation (boiling) common	Ambient to 10 000 kPa (100 bars), H ₂ O boiling common, CO ₂ boiling possible
Stable isotope data — (relative to SMOW)	+5 to +11‰, heavy relative to local or meteoric water	–15 to 0‰, light, same as or slightly enriched relative to meteoric water
$\delta^{18}\text{O}$ H ₂ O		
$\delta^{18}\text{O}$ qtz	+13 to +18‰	–5 to +20‰
D H ₂ O fluid inclusion	–160 to –90‰, north-to-south latitude-dependent	–150 to –40‰, north-to-south latitude-dependent
²⁰⁷ Pb	Low values in ore; uniformly consistent in district, primitive lower-crust source	Markedly radiogenic, mixed source

Principal References:

Hayba *et al.* (1985), Nesbitt *et al.* (1986), Heald *et al.* (1987), Dowling & Morrison (1989), Nesbitt and Muehlenbachs (1989), Nesbitt (1988, 1991), Kerrich (1989), Henley (1991), also Ken Dawson, personal communication, and other unpublished sources.

TABLE 7-3

Major British Columbia Mesothermal and Epithermal Deposits

NAME	DEPOSIT TYPE	AGE	SIZE (tonnes) P = Produced R = Reserves	GOLD Recovered kg	GOLD Reserves kg	SILVER kg
MESOTHERMAL						
1. BRIDGE RIVER CAMP: Bralorne, Pioneer, Congress, Reliance, Wayside, Minto	Quartz veins	L Cretaceous	P 7 317 300	129 953	17 617	31 180
2. ROSSLAND CAMP: Le Roi, Centre Star, Josie, War Eagle, etc.	Cupriferous sulphide veins	E-M Jurassic ± Eocene ?	P 5 623 200	85 387		107 020
3. CARIBOO-BARKERVILLE CAMP: Cariboo Gold Quartz, Island Mountain (Aurum), Mosquito Creek	Quartz veins and sulphide replacements	E Cretaceous and/or M Jurassic ?	P 2 746 300	38 295	1089	5144
4. SNIP	Shear hosted quartz-carbonate and sulphide veins	E Jurassic	R 936 000		28 080	
5. SHEEP CREEK CAMP: Queen, Reno, Kootenay Belle, Gold Belt, Nugget, Vancouver	Quartz-sulphide and sulphide veins	E Cretaceous	P 1 531 900	23 685	2302	9117
6. FRASERGOLD	Quartz veins and sulphidized phyllitic wallrocks	M Jurassic	R 11.8 to 13.6 million estimate		21 835	
7. SULPHURETS CAMP:** Brucejack Lake zones	Quartz veins and stockworks	E Jurassic	R 1 393 815		17 170	874 420
8. ZEBALLOS CAMP: Spud Valley, Privateer, etc.	Quartz veins	Eocene to Oligocene	P + R 1 078 936	8587	5355	P 3737
9. CASSIAR CAMP: Erickson Gold, Taurus (Hanna), Cusac, Vollaugh	Quartz veins	E Cretaceous	P 836 436	7489	6138	5405
10. SURF INLET	Shear zones	E Cretaceous ?	P+R 969 835	12 096	620	6258
11. RED MOUNTAIN (MARC zone)	Sulphide veins	E Jurassic	R 846 400 estimate		10 737	
12. GOLDEN BEAR Golden Bear and Fleece zones	Silicified fault zones and breccia	E-M Jurassic	R 541 610		9200	
TRANSITIONAL						
1. ESKAY CREEK * 21B, 21C, Pumphouse Creek, TOK and 21A zones	Massive sulphide and quartz-sulphide stockworks	E-M Jurassic	R 5 162 790		118 885	4 265 940
2. EQUITY SILVER	Sulphide stockworks and replacement	Eocene	P + R 32 154 000	16 938		2 293 230

A continuum between mesothermal and epithermal deposits is conjectural; it should exist between the hypothermal and epithermal environments if the depth-zoning premise is correct. Hot, high pressure mineralization in epizonal environments can be evident where deep erosion exposes large vertical sections through mineralized systems, sometimes right into their intrusive roots (see Sillitoe, 1989 and 1991a). There we can use the term 'Transitional' in place of leptothermal to describe high temperature and pressure mineralization associated with the

emplacement of plutonic rocks, commonly copper-molybdenum bearing porphyry stocks in epithermal environments. In transitional deposits much of the hydrothermal fluid is typical of that in epithermal deposits but at times, or locally, the fluids are hotter and pressures exceed hydrostatic, well in excess of epithermal conditions. The transitional environment might simply refer to a high-level or epizonal, sub-volcanic setting for *intrusion-related* hydrothermal mineralization without regard for any temperature constraints.

TABLE 7-3 — Continued

Major British Columbia Mesothermal and Epithermal Deposits — Continued

NAME	DEPOSIT TYPE	AGE	SIZE (tonnes) P = Produced R = Reserves	GOLD Recovered kg	GOLD Reserves kg	SILVER kg
EPITHERMAL						
1. PREMIER GOLD (Silbak Premier)	Quartz-carbonate veins, stockworks and breccia	E Jurassic	P + R 10 686 880	56 117	14 805	1 269 125
2. CINOLA	Quartz stockworks and phreatomagmatic breccia	Miocene	R 23 804 535		58 763	
3. TOODOGGONE CAMP: Lawyers, Shas, Al, Baker, Mets, etc. LAWYERS	Quartz veins, stockworks and breccia	E Jurassic	P + R 3 507 573	2720	18 037	1 032 750
			P + R 1 771 971	1510	11 447	426 127
4. SULPHURETS ** Snowfield zone, Sulphurets Breccia	Large pyritic propylitic alteration zones	E Jurassic	R 7 000 000 Large geological resources >20mt		18 0600	
5. BLACKDOME	Veins and breccia	Eocene	P 333 800	7692		22 605
6. BIG MISSOURI**	Quartz-carbonate- sulphide breccia veins and lenses	E Jurassic	P + R 2 243 300	1816	4717	P 1638
7. MOUNT WASHINGTON** Domineer-Lakeview	Sulphide-quartz veins and replace- ments in flat faults, breccia	Eocene to Oligocene	P + R 787 437	131	3904	P + R 25 880
8. VAULT	Fault breccia, detachment ?	Eocene	R 151 200		2126 estimate	

* Genetic classification uncertain — probably volcanogenic massive sulphide with underlying feeder zone epithermal quartz-sulphide veinlets, stockworks and breccia

** Genetic classification uncertain — may be mesothermal type or intrusion-related transitional type deposit. Sources of Information: Ministry files, unpublished company reports, Schroeter *et al.* (1989) and Schroeter and Lane (1991).

From fluid inclusion and geothermal data, geological reconstructions and other information, we now know that the thermal conditions defined by Lindgren for his depth zoning scheme are inadequate and locally invalid, as is a strictly magmatic origin for all hydrothermal fluids. None the less, the use of depth zoning terms remains entrenched because they provide a useful geological reference point to which crustal environments and ore deposits can be spatially related at the time of mineralization — the paleosurface. However, identification and definition of the paleosurface is not always easy and its significance during mineralization can be obscure.

DEPOSIT DISTRIBUTION

A pronounced clustering of various types of gold deposits is evident along the western margin of the Omineca Belt and along both the western and eastern margins of the Coast Belt (Figure 7-1). The greatest density of known gold and most other types of metal deposits is in the southern, most intensely prospected and developed part of the province.

Many lode gold deposits and most of the larger placer districts are associated with major structural breaks, notably the terrane boundaries of the Bridge River, Cache Creek and Slide Mountain oceanic volcanic terranes (Hodgson *et al.*, 1982). These oceanic terranes consist of disrupted ophiolitic or composite volcanic arc-marine clastic assemblages intruded by dioritic or granitic intrusions. The major deposits in this setting, such as in the Bridge River, Atlin and Cassiar areas, are mesothermal gold occurrences similar to Archean greenstone or California Mother Lode-type deposits. Genetically related mercury and antimony mineralization is found peripheral to the gold deposits in some districts, for example, Bridge River, or occurs along strike in major fault zones such as those in the Pinchi and Stuart Lakes areas (Madu *et al.*, 1990).

Replacement zones in clastic or carbonate rocks near major faults along oceanic terrane boundaries are also considered to be mesothermal. One such occurrence is found at the Carolin mine where albitized, pyritic Jurassic clastic rocks are mineralized (Ray, 1990). There, initial host rock per-

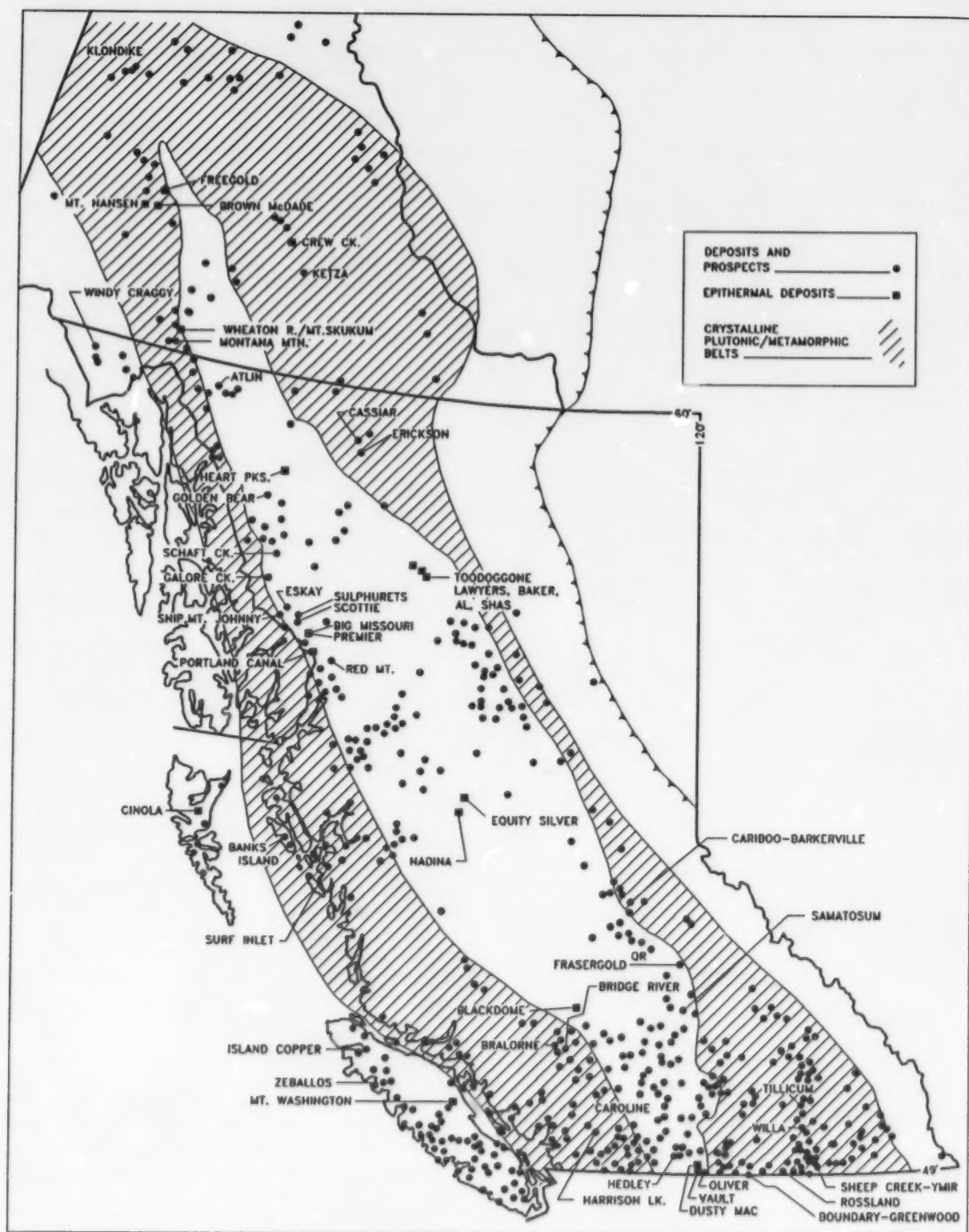


Figure 7-1. Lode gold deposits in the Canadian Cordillera; data from MINFILE and CANMINDEX data files.

meability rather than later quartz vein development appears to have controlled gold deposition. Similar lithologically controlled, structurally induced hydrothermal activity appears to be responsible for the older pyritic replacement orebodies in Paleozoic metasedimentary rocks at the Cariboo Gold Quartz deposits. These deposits have multiple-stage ores related first to Middle Jurassic sulphide replacements, followed by superimposed Early Cretaceous quartz veins (Andrew *et al.*, 1983; Robert and Taylor, 1989). Elsewhere, for example the Rossland district and Scottie mine near Stewart, mesothermal sulphide veins in volcanic rocks are characterized by high temperature iron-magnesium silicate alteration assemblages with pyrrhotite-rich, base metal mineralization.

Other Cordilleran mineral deposits associated with mesothermal gold deposits in oceanic terranes are gold placers, some containing platinum-group elements and polymetallic massive sulphides, mercury and antimony, asbestos, nephrite jade and manganeseiferous chert deposits.

Epithermal and transitional deposits are found in regional or local extensional settings in Mesozoic and younger (notably Eocene) volcanic successions. They are also associated with high-level plutons, particularly their altered margins, in rocks of the Insular and Intermontane belts. Other favourable sites of mineralization are the repeatedly disrupted transverse structural zones in Mesozoic and Tertiary volcanic regions such as the Skeena and Stikine 'arches', where long-lived deep fracturing has facilitated intrusion of both mesozonal plutons and epizonal stocks. Many of the higher level intrusions are intruded into their coeval and consanguineous volcanic products.

Cordilleran epithermal deposits are similar to those found elsewhere around the Pacific margin (Bonham, 1985). Virtually all the deposits are volcanic hosted. The geological environments they most closely resemble are those of the young volcanic island arc terranes of the southwest Pacific (Sillitoe, 1989). Some, such as Blackdome mine resemble the Tertiary age bonanza deposits of the southwestern U.S.A. (Heald *et al.*, 1987). Another deposit, Cinola, is a Miocene or younger hot spring-related deposit (Tolbert and Froc, 1988; Christie, 1989). It is similar to the hot spring and geothermal occurrences described by Berger and Bethke (1985) and others.

A notable difference to epithermal deposits in most other regions is that many Cordilleran deposits are Mesozoic in age (*e.g.*, Toodoggone and Stewart areas). They are hosted by Early Jurassic calc-alkaline to alkaline (shoshonitic) andesites which formed in accreted island-arc or back-arc depositional settings. Subaerial rocks in these Mesozoic environments are subordinate to subaqueous volcanic units but both epithermal and porphyry-style

mineralization are found in subaqueous as well as the subaerial successions.

Deposits not found to date in the Cordillera are the sediment-hosted, fine-grained, disseminated 'Carlin-type' deposits in calcareous sedimentary rocks (Tooker, 1985), nor 'detachment-type' deposits associated with flat, listric-normal faults in or bounding metamorphic core complexes (Wilkins, 1984). Recently the Dusty Mac deposit and possibly a number of others in southern Quesnellia have been interpreted to be small, Tertiary 'detachment-type' gold deposits (Tempelman-Kluit and Parkinson, 1986).

AGE OF GOLD MINERALIZATION

The timing of gold deposition in the various morphogeological belts and terranes is shown on Figure 7-2. The age data are compiled mainly from a compendium of radiometric dates determined at The University of British Columbia. Clearly, much of the gold in numerous vein, some skarn (Hedley), breccia (Willa), porphyry copper (Mt. Polley, Galore Creek or 'Stikine Copper', Copper Mountain/Similkameen) and related propylitic replacement deposits (QR) is associated with latest Triassic to Early Jurassic pre-accretionary and accretionary magmatic activity (Dawson *et al.*, 1992). The gold mineralization is related to both volcanic and mesozonal to epizonal plutonic hydrothermal systems in volcano-plutonic island arcs. The most notable precious metal deposits in older volcanic rocks are those in the Stewart-Iskut area (Premier mine, Sulphurets and Eskay Creek). Closer to the ancestral continental margin, back-arc or marginal basin volcanism and coeval plutonism deposited calcalkalic to alkaline (shoshonitic) subaerial rocks in the Toodoggone area with associated typical volcanic-hydrothermal porphyry copper-gold and epithermal precious metal systems (Diakow *et al.*, 1991).

Numerous small, gold and silver-bearing polymetallic veins and replacements are related to 150 to 100 million-year-old plutons or structural/metamorphic culminations that span accretionary to post accretionary tectonic events. Examples are the gold camps of southern Quesnellia (Oliver, Fairview, Ymir, Frasergold) and many other small deposits elsewhere (Cassiar, Sheep Creek, Dentonia, Banks Island, Surf Point, Surf Inlet). Curiously, the central zones of the very extensive crystalline accretionary 'tectonic welts' — the Omineca and Coast belts are not well mineralized. This is possibly because the high-grade metamorphic core zones have been uplifted and rocks are too deeply eroded to preserve any hydrothermal pathways and deposits. Instead, mineralization is more evident in or near the smaller, generally younger, epizonal satellitic plutons or shallower parts of major fault zones bounding the margins of the tectonically thickened crystalline belts.

The large Cordilleran terrane-bounding faults in the eastern Intermontane and Omineca belts, particularly those that juxtapose oceanic rocks with

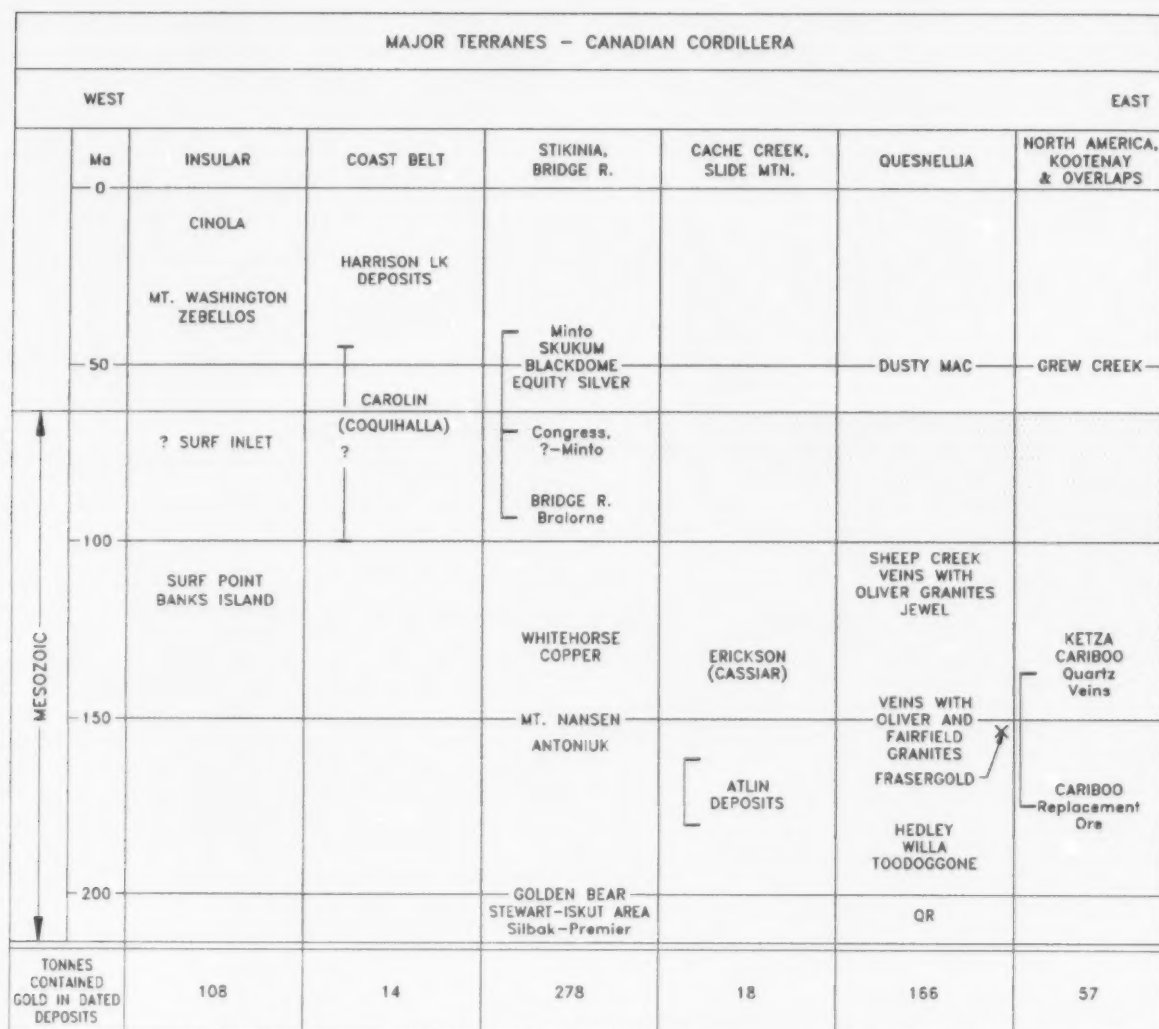


Figure 7-2. Radiometric ages of gold mineralization in major tectonophysiographic belts; main data source is *The University of British Columbia geochronology file*.

other terranes, are zones of Middle Jurassic and somewhat younger accretionary tectonic overlap. They have been interpreted to have large, post-mid-Cretaceous right-lateral strike-slip displacements. A number of the fault systems focused large-scale hydrothermal fluid migration and contain mesothermal gold and related mercury and antimony occurrences. The oldest dated mineralized systems are the Early to Middle Jurassic Golden Bear and Atlin deposits of northern Stikinia. Similar occurrences are found in the Early Cretaceous Cassiar district formed after collision of Quesnellia with North America. These are comparable in tectonic setting, origin and age to the California Mother Lode and other orebodies of the Sierra Nevada foothills. The California deposits range in age from 140 to 110 Ma, with mean and median ages between 120 and 115 Ma

(Bohlke and Kistler, 1986). This suggests that major tectonic activity with a related gold-forming metallogenic epoch occurred along a large portion of the western margin of North America at the end of the Jurassic period and during Early Cretaceous time. These mineralizing episodes together with widespread evidence for synchronous or slightly older metamorphic events might signify that major perturbations took place in Pacific (Farallon and Kula) and North America plate interactions in the Middle to Late Jurassic.

During Late Cretaceous time wrench faulting also took place along the reactivated Fraser and subsidiary fault systems. It initiated deep fluid-flow resulting in deposition of the large mesothermal vein systems of the Bridge River camp. Radiometric dating and isotopic studies suggest (Leitch and Godwin, 1988;

Leitch *et al.*, 1991a) that gold mineralization took place between 91 and 85 Ma following metamorphism and during intrusion and major structural disruption of the region. Some overprinting and younger mineralization to the north and east occurred during a series of protracted intrusive and tectonic events that continued episodically to 44 Ma, and possibly later (Leitch *et al.*, 1991a; Schiarizza and Gaba, in preparation). The Late Cretaceous to Early Tertiary mineralizing period coincides with emplacement of plutonic rocks and dikes and uplift in the Coast Belt. A similar geologic setting has been described in the Coquihalla gold belt 175 kilometres to the southeast by Ray (1990). There, geological evidence suggests post-Early Cretaceous but pre-late Eocene mineralization.

Tertiary post-accretionary precious metal mineralization throughout the Cordillera is related to conti-

nental (terrestrial) volcanism or epizonal to sub-volcanic plutonism, generally in zones of extensional tectonism. Eocene volcanic-hosted epithermal veins comprise the Montana Mountain and Grew Creek deposits, in Yukon, Blackdome mine and the silver-gold rich Equity Silver porphyry-related transitional orebody (Cyr *et al.*, 1984). One of the youngest major deposits is the Cinola epithermal Miocene hot spring system with mineable reserves of 24.8 million tonnes with 2.45 grams per tonne gold. It is hosted by Tertiary conglomerate and is associated with a Miocene rhyolite dike (Champigny and Sinclair, 1982). Other young intrusive-related occurrences are quartz veins and breccia-stockworks in or adjoining late Eocene or Oligocene intrusions near Zeballos and Mount Washington on Vancouver Island and the Oligocene-Miocene stocks near Harrison Lake (Ray, 1986).

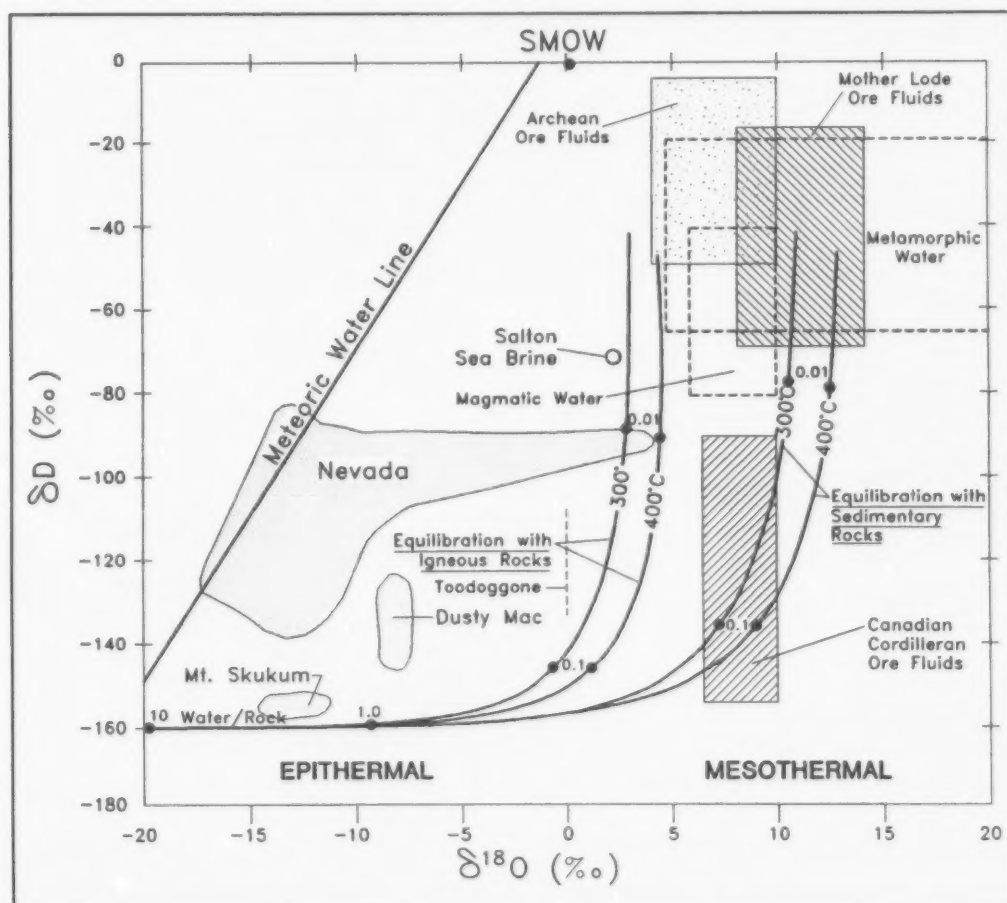


Figure 7-3. Light stable isotope diagram showing bulk analyses of hydrothermal fluid compositions and evolution paths; adapted from Kerrich (1989, 1990a) and Nesbitt and Muehlenbachs (1989).

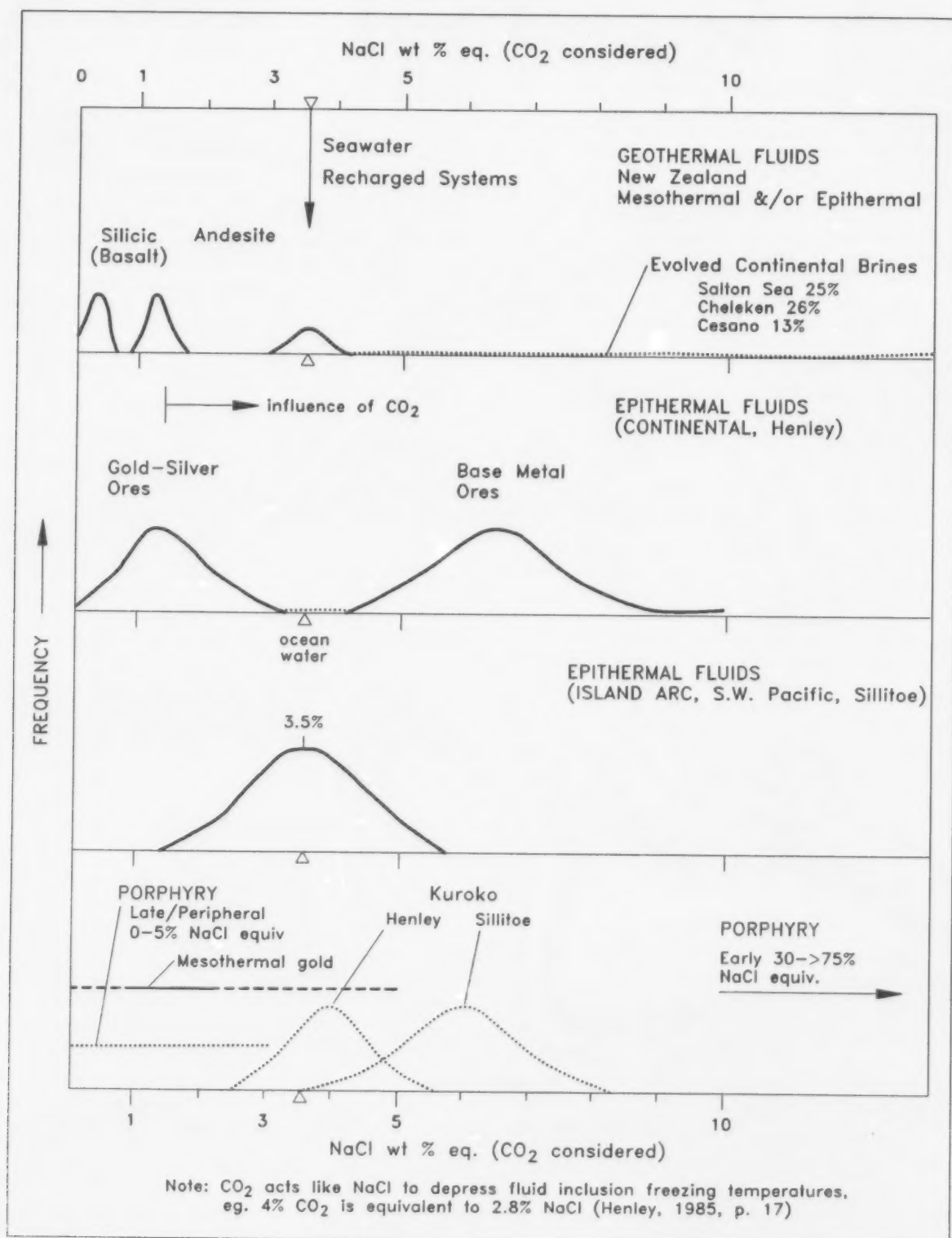


Figure 7-4. Fluid compositions in relation to hostrock and crustal environment sources; schematic after Henley (1985, 1991), Hedenquist and Henley (1985) and Sillitoe (1989).

HYDROTHERMAL FLUID SOURCES AND GOLD SOLUBILITY

HYDROTHERMAL FLUID SOURCES

Depth-zoning classification dictates that two different fluid systems are involved in mesothermal and epithermal mineralization. Light stable isotope studies, mainly oxygen-18 and heavy hydrogen (deuterium), of fluid inclusions and some ore fluids, provide perhaps the most useful insights into the fluid sources (Figure 7-3). They confirm that hydrothermal fluids are, indeed, isotopically different, at least at their source. But isotopically distinct waters all behave the same way as hydrothermal solutions in terms of their solution chemistry. Their isotopic composition has nothing to do with their ability to transport metals. The variations and differences between ore deposits must, therefore, be due to local geological conditions or fluid attributes other than their isotopic make up. Compositions of a number of hydrothermal solutions are shown on Figure 7-4 and in Table 7-4. The amounts of dissolved constituents are so small that, with rare exceptions, only slight differences are evident between the various gold bearing hydrothermal solutions. They are all predominantly aqueous, dilute solutions with comparable temperature, salinity, pH, dissolved metal and gas contents.

Mesothermal deposits in the Cordillera shown on Figure 7-3 are genetically similar to those elsewhere, including the Archean greenstone-hosted and Mother Lode-type deposits. They have been interpreted to form from highly evolved fluids that are derived predominantly from mixed source meteoric waters combined with fluids expelled from metamorphosed sedimentary rocks. The complex history

of mesothermal deposits, as is becoming evident from detailed isotopic studies (Taylor *et al.*, 1991), is apparently due to interactions of different generations and multiple sources of mineralizing and post-ore fluids. Epithermal hydrothermal solutions in many cases are unequivocally meteoric in origin. On the other hand, a number display a wide range of compositions that permit virtually any combination of fluid sources to be postulated. In addition to meteoric waters, epithermal solutions can contain magmatic fluids, seawater, evaporite and connate waters, deep brines, metamorphic fluids and even far-travelled mesothermal-source fluids.

Fluid sources for the main types of gold deposits, are shown on Figures 7-3, 7-4 as discussed by Henley (1985), Kyser and Kerrich (1990) and Sillitoe (1989). There can be virtually complete overlap between geothermal fluids and the continental and island arc epithermal fluids. Examples of major fluid sources are:

- **Geothermal fluids** as described in New Zealand from the Taupo Volcanic Zone and the Alpine fault zone: *epithermal* — meteoric ± seawater; *mesothermal* — meteoric with variable seawater recharge; possibly some deep-crustal fluids with metamorphic and possibly some magmatic input are involved.
- **Continental epithermal fluids** found throughout western North America, the Andes and other continent-margin volcanic belts: dominantly meteoric for gold-silver deposits; mixed sources in base ± precious metal deposits involve meteoric plus saline fluids derived from evaporite solutions or brines. Locally high temperature, magmatic-source fluids may be important in early stages of mineralization.

TABLE 7-4

Composition of Metal-Depositing Hydrothermal Fluids

Fluid Source	Broadlands, N.Z. ¹ Geothermal fluid	21°N East Pacific Rise ² Seafloor vent	Explorer Ridge ³ Seafloor vent	Salton Sea ⁴ Deep continental brine
T °C	260	306	350	300-340
NaCl wt %	0.5 ? (estimated)	3.5	3.7-6.4	23
pH	6.3	3.6	4.8	4.6-5.5
Cl	1188	18932	19670	155000
CO ₂	4300	250	—	130 ±
SiO ₂	552	1052	900	400
H ₂ S	64-120	253	—	20-30
Au ppb	1.5	to 0.2	to 0.1	0
Ag	8	2.7	30	1 ±
As	5700	17	30	12
Sb	200	—	0.7	0.4
Hg	—	—	—	60
Fe	226	79710	1800	2145
Cu + Zn + Pb	12	5612	1110	617

All in ppm except pH and where noted; some values shown as means recalculated from original data.

Sources of information:

¹ Henley & Hedenquist, 1986;

^{2,3} Hannington & Scott, 1989;

⁴ White, 1968.

- **Island arc epithermal** from around the circum-Pacific belt: meteoric with significant early seawater input or late seawater recharge, for example at Ladolam, Lihir Island (Davies and Ballantyne, 1987) and White Island, New Zealand (Giggenbach, 1986, 1987, 1988). Commonly some magmatic input is evident, especially where acidic hot springs and solfataras are present.
- **Kuroko** (volcanogenic massive sulphide deposits; see Ohmoto and Skinner, 1983; Höy, this volume): dominantly seawater; some magmatic contribution may be present.
- **Porphyry copper** (and 'transitional' deposits): early fluids are mainly magmatic including condensed gas and CO₂-rich phases; later, peripheral and distal hydrothermal fluids are mixtures of varying amounts of meteoric, seawater and magmatic solutions.

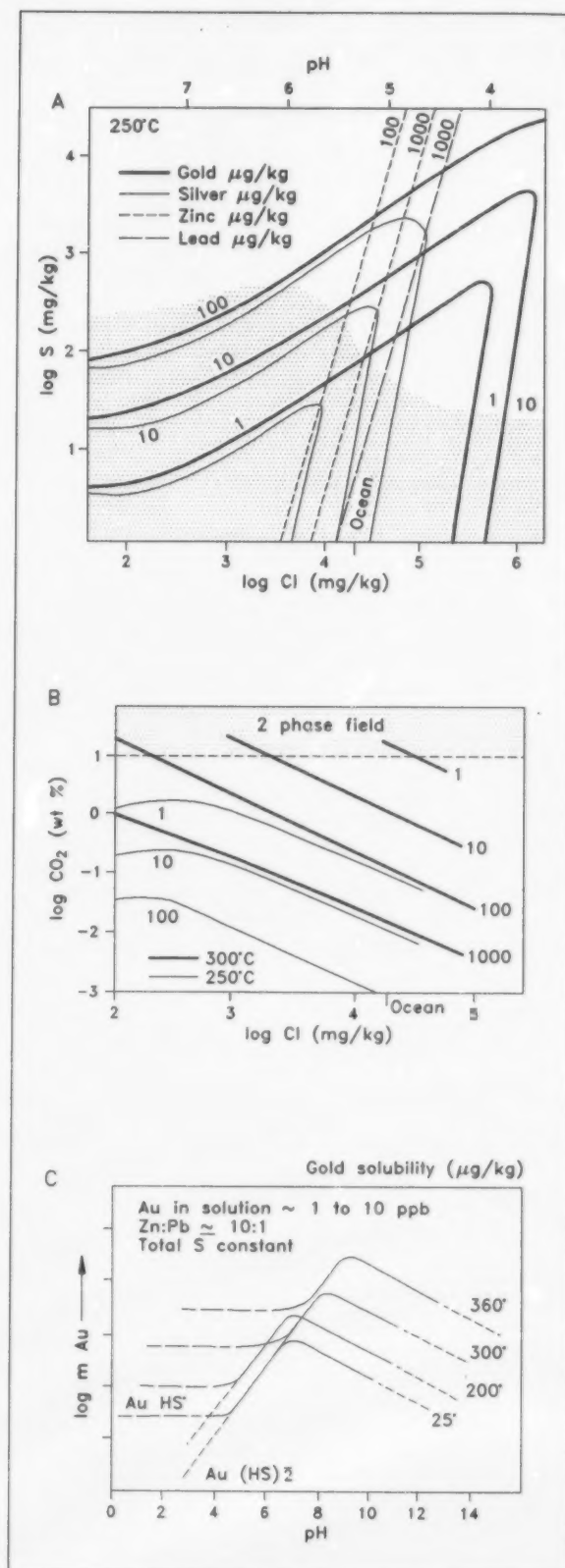
The source and origin of hydrothermal fluids in mineral deposits usually can only be speculated upon. Compositional differences in ore forming fluids are generally slight and variations between gold ores deposited from apparently similar fluids are due to site-specific, possibly unique fluid and fluid-rock reactions that take place as the hydrothermal solutions migrate and evolve. In practical terms, the origin of fluids is less important in determining the style of mineralization than is the amount of fluid available, its level of ascent, residence time in the upper crust and cooling history — all functions of the local geological environment.

GOLD SOLUBILITY AND DEPOSITION

SOLUBILITY

In view of the importance of gold and gold deposits, it is surprising how little study the hydrothermal chemistry of gold has received until recently. Seward's 1973 study, updated in 1984 and 1989, stood as the landmark reference on the subject until his 1991 summary (Seward, 1991). Other recent data about gold transport and deposition are available including many discussions concerned with boiling as the fundamental depositional mechanism. Excellent recent summaries are found in *Economic Geology Monograph 6* (1989) which contains a review of gold hydrothermal chemistry by Seward

Figure 7-5. Gold solubility (rock or mineral buffered). **A** — Solubility map of gold, silver and base metals at 250°C in chloride-sulphide solutions; stippled area shows composition range of fluids in active geothermal areas, from Henley (1991). **B** — Solubility of gold at 250 and 300°C in chloride-sulphide-CO₂ solutions. Stippled area shows region with pressure-dependent two phase conditions, from Berger and Henley (1989). **C** — Gold solubility from 25 to 360°C as function of pH. Curves show cumulative maximum solubility of dominant Au-HS species AuHS⁰ and Au(HS)⁻², from Seward (1991).



and a study of auriferous massive sulphide deposition by Hannington and Scott (1989). Epithermal (geothermal) fluids undergoing boiling are discussed by Drummond and Ohmoto (1985), Krupp and Seward (1987) and Spycher and Reed (1989).

A major breakthrough in our understanding of gold solubility and transport came in 1983 from studies of the Broadlands geothermal system, New Zealand, (Brown, 1986). There, a deep well (BR22) tapped a 260°C gold-bearing hydrothermal fluid in the zone of boiling. Flashing of a controlled amount of steam in a gas separator at 180°C resulted in the precipitation of coatings on pressure plates and pipes of essentially pure chalcopyrite containing 21 per cent copper, 4.5 per cent gold and 6.9 per cent silver. This allowed the concentration of solutes (notably gold) to be calculated for the ore fluid from the site of ore deposition rather than from surface sources where hydrothermal fluids in hot springs or geothermal pools are greatly diluted by mixing with ground waters.

The important factors about hydrothermal transport of gold summarized by Seward (1991) are:

- Gold is concentrated in the order of 1 to 11 ppb in deep aquifers, not the 0.00004 to 0.04 ppb range that was postulated from earlier studies of surface waters;
- Gold transport in typical (high temperature, low oxidation state) hydrothermal fluids is almost entirely by reduced bisulphide complexes. The three main gold complexes and the nature of their hydrothermal solutions are:
 AuHS^0 — acid pH
 $\text{Au}(\text{HS})_2^-$ (dihydrosulphidogold) — near-neutral to weakly alkaline pH
 $\text{Au}_2(\text{HS})_2^-$ — alkaline pH

The solubility maximum over a wide range of temperature appears to be mainly due to presence of $\text{Au}(\text{HS})_2^-$ in near-neutral pH solutions. However, stability of this complex shifts to more alkaline conditions with increasing temperature. Higher temperature fluids (in excess of 300°C) with pH in the range from 5 to 6.5 because of buffering by mineral equilibria, will typically transport less gold as $\text{Au}(\text{HS})_2^-$ and other species, such as AuHS^0 , will be dominant (Seward, 1991, pages 45–51). The temperature-pH effects on the solubility curve of the major gold complexes is shown on Figure 7-5a.

- Concentration of gold in chloride complexes (AuCl_2^-) is exceedingly small (around 1.2×10^{-7} ppb, approximately six orders of magnitude less than dihydrosulphidogold complex). Where unusually high salinities near halite saturation exist and temperatures exceed 400°C or so, gold chloride complexes may be important (Henley, 1991).
- Other ligands (As, NH_3 , Sb, SCN, Te) and colloids may transport gold (Seward, 1991) but their importance is uncertain and probably minor.

Base metal transport, in contrast to gas-dependent reduced sulphur gold complexing, is mainly by chloride complexes in addition to some bisulphide and sulphide complexing and is, therefore, largely salinity dependent. Fluid salinity is a function of fluid source (discussed above), fluid- and fluid-rock cooling reactions (discussed below) and to a lesser degree, host rock type (Figure 7-4). A consistent pattern in epithermal adularia-sericite systems recognized by Hedenquist and Henley (1985) shows low salinities for gold-silver deposits and greater than seawater salinities for base metal-silver±gold deposits (Henley, 1991).

Metal transport in hydrothermal (epithermal) systems is summarized by Henley (1991). He states that the essential chemical distinction between precious metal and base metal-silver deposits is because **solubility of gold is directly proportional to the concentration of reduced sulphur (H_2S) in solution but is inversely proportional to salinity**. In contrast, base metal transport is by chloride complexing and is, therefore, inverse to the behavior of gold. The relationship is shown on Figure 7-5a. Gold transport in the hydrothermal fluid is dependent on H_2S concentration — a function of total gas content in the solution, Figure 7-5c. The H_2S content is inversely related through fluid-mineral equilibria to the concentration of CO_2 , a function of f_{XO_2} -mCl-temperature, as shown on Figure 7-5b. As summarized by Henley, 1991, page 153: "The implication of these data is clear — the solubility of gold in crustal fluids in volcanic terranes is strongly linked to CO_2 concentration and to temperature in the alteration-buffered roots of hydrothermal systems." Henley further draws attention to the importance of magma degassing as a source of metals (and fluids) in the development of both epithermal and porphyry copper deposit deposits (Henley, 1991, page 153; see also Sillitoe, 1991a). Other relationships suggested by Figure 7-5a and field observations are that copper and silver in hydrothermal solutions behave intermediately between base metals and gold. Silver accompanies gold in low-salinity fluids, when salinity increases, silver accompanies base metals. In essence, gold and silver are transported by reduced sulphur, gas-rich, low-salinity hydrothermal solutions; base metals along with some silver are transported by higher-salinity solutions with lower gas contents. Silver-gold ratios, therefore, can be used as an indication of salinity contents of the ore-depositing fluids — low salinity fluids produce $\text{Ag}/\text{Au}=0.1$ to 10, higher salinity can result in $\text{Ag}/\text{Au}=10$ to 1000.

MINERAL DEPOSITION

Deposition from hydrothermal fluids is controlled by four fundamental processes (Barnes, 1979): temperature changes — usually cooling; pressure changes — usually a drop in fluid pressure from lithostatic to hydrostatic; chemical reactions due to

mixing of solutions — generally dilution and redox reactions; and chemical reactions between wallrocks and solutions — commonly fluid buffering due to mineral equilibrium reactions during hydrolysis and hydration. The first three points are particularly important for epithermal deposits where there are large physical and chemical vertical gradients. Wallrock-fluid interactions are more significant for mesothermal, a few highly sulphidized epithermal deposits and some sedimentary rock-hosted deposits, for example, the Carlin-type disseminated gold deposits.

The mineralization processes and conditions in which they take place are determined and controlled by the *geological environment*. The geological environment determines mainly: sources of heat and rates of cooling (temperature); dynamics of fluid flow and mixing (dilution); structural events leading to depressurization with attendant degassing by boiling (phase separation); oxidation/reduction (redox reactions) and fluid-wallrock interactions governed by the reactivity of ore hostrocks. These have been discussed at length in a wealth of recent and older literature. The topic is discussed by Henley *et al.* (1984) and summarized succinctly and simply by Guilbert and Park (1986, pages 126–133) and Henley (1991, pages 155, 156). The following discussion is extracted mainly from these three sources:

Cooling takes place when hydrothermal fluids rise towards the surface along a decreasing geothermal gradient. Most commonly, metal bearing fluids mix with cooler, more dilute solutions. Alternatively and less commonly, fluids can be heated during migration by mixing with hotter fluids produced by volcanic activity and magma emplacement. Conductive heat loss through interaction with cooler wallrocks can be important in deeper deposits but is of little consequence in the high-permeability, open-space-filling epithermal-type deposits. Cooling also takes place efficiently where gas is evolved by boiling or by phase separation (effervescence) if the gas is effectively removed or conveyed away from the hydrothermal system.

Boiling describes the temperature-pressure-related condition at which a liquid evolves vapour and $P_{\text{liquid}} = P_{\text{gas}}$. This can take place adiabatically (without heat gain or loss), and occurs when pressurized fluids pass into more permeable zones such as faults, breccias or porous lithologies, or pressure release to surface takes place due to faulting or other structural disruptions. It can occur over a large vertical distance. For example, fluids with a few per cent CO_2 lie very close to the two phase envelope to depths of several kilometres so they can boil from depth virtually all the way to the surface. Boiling may also occur when cold water mixes with gassy, hot water. The major importance of boiling is that it leads to phase separation. In an open system the phase

separation and the physical removal of gases from the liquid phase results in substantial chemical changes in the hydrothermal solutions. Boiling without phase separation does very little to change the chemical composition of the fluid.

In addition to cooling by vapour loss, boiling or phase separation has a major effect on the chemistry of the fluid phases. Loss of volatiles initially removes H_2S , CO_2 and other components more volatile than H_2O . The residual fluid pH increases due to consumption of H^+ ($\text{H}^+ + \text{HCO}_3^- = \text{CO}_2\text{v} + \text{H}_2\text{O}$ and $\text{H}^+ + \text{HS}^- = \text{H}_2\text{Sv}$) as well as the loss of acidic gasses such as HF and HCl. Calcite deposition is a common indicator of boiling and alkaline fluid conditions ($\text{Ca}^{+2} + 2\text{HCO}_3^- = \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O}$). Also *adularia* forms under alkaline conditions and provides a mineralogical indicator that boiling could have taken place. A 'lattice' texture commonly seen in epithermal deposits is silica pseudomorphs after bladed calcite. This texture forms after calcite that is initially deposited because of CO_2 loss and calcite supersaturation, later dissolves due to its retrograde solubility and is replaced by silica which becomes oversaturated in solution as temperatures decrease. The texture is frequently (and rightly or wrongly) attributed to boiling in the hydrothermal solutions.

Large amounts of silica, commonly chalcedony, can be deposited from extensively boiled supersaturated solutions. Near surface, the silica is deposited as amorphous and opaline-chalcedonic sinters or chalcedonic veins. At slightly greater depth, banded silica veins (with *adularia* and/or calcite) are more prominent due to 'transient pressure changes in the vein environment' (Henley, 1991, page 156). The following sequence of silica deposition (Fournier, 1985) from high to low-temperature silica polymorphs is commonly seen: crystalline quartz $>200^\circ\text{C}$ — chalcedonic quartz $150^\circ\text{C} \pm$ — opal $120^\circ\text{C} \pm$ — amorphous silica. At high temperatures (above 320°C) or where fluids are diluted by cool groundwaters with little silica in solution, the silica may be undersaturated or concentrations may be so small that no major silicification can take place in these parts of the hydrothermal system.

A thermochemical study of a boiling Broadlands-type geothermal fluid by Spycher and Reed (1989) provides especially useful insights into hydrothermal depositional processes and products. They consider *boiling* and *acidification* as the main depositional mechanisms responsible for the sequential, spatially (and chronologically) separate base, precious and mercury-arsenic-antimony (the 'volatile' metals) mineralization. They describe the following succession of depositional events:

1. **Boiling** resulting in pH increase, causes precipitation of base metals. The initial increase in gold solubility due to pH increase is offset and supplanted by hydrogen sulphide loss to the gas phase, leading to electrum deposition. Interestingly, Spycher and

Reed consider that heat loss to or from wallrocks controls the amount of boiling (and therefore, deposition) in these systems. At lower temperatures and decreased (intermediate) pH as boiling proceeds, arsenic and antimony, which are present in the aqueous fluid as thiosulphides, precipitate with copper and lead sulphides and silver sulphosalts. Mercury fractionates into the gas phase and is deposited as cinnabar between 80 and 100°C. Arsenic and antimony are transported in the aqueous phase until boiling to dryness takes place. Only then are they transported by the gas phase to deposit antimony as stibnite below 220°C and arsenic as realgar below 130°C.

2. **Acidification** by acid-sulphate waters is attributed by Spycher and Reed mainly to addition of H_2SO_4 from magmatically derived sulphur dioxide gas. Note that the emplacement and devolatilization of magma at depth is not always demonstrable nor necessary in every geothermal area. Acidification by fluid mixing with refluxing acid near-surface water of steam-heated hypogene origin as well as acidic solutions of supergene origin is very effective and does not require any magmatic gas contribution. A discussion of the contrasting origins and exploration significance of acidic near-surface fluids is given in the section dealing with hydrodynamic regimes in epithermal deposits.

The following depositional sequence resulting from acidification (and boiling) is set out in Spycher and Reed's summation: gold-rich electrum or gold with copper sulphides are deposited (200–101°C) followed by sulphosalts (150–101°C), enargite (101°C) and finally, orpiment and stibnite (90°C). This type of acidification-induced ore deposition commonly forms vuggy, silica-rich 'sponge rocks' in a downward-zoned sequence of enargite-covellite-tetrahedrite-chalcopyrite-pyrite mineralization. Typical acid-sulphate deposits, also known as enargite-, advanced argillic, or kaolinite-alunite-type (see Tables 7-2 and 7-5, are exploited at Summitville, Colorado, El Indio in Chile and Lepanto, Phillipines and are common occurrences elsewhere in the Andes and a number of western and southwest Pacific island arcs. They are discussed further in the section on epithermal deposits in this paper.

The systematics of gold transport in boiling solutions are summarized by Seward (1989, 1991). Closed-system adiabatic boiling initially causes an increase in gold solubility due to increased pH but this is countered by loss of reduced sulphur that eventually leads to deposition of gold. Continued boiling and cooling over the temperature interval from 250 to 180°C would precipitate much of the gold (Seward, 1991, page 54). Conductive cooling would also precipitate gold over a similar temperature range but this would invariably take place over a very large fluid pathway and result in low-grade deposits. The most efficient ore-depositing mecha-

nism is open-system boiling accompanied by escape of the volatile phase(s). Under these conditions gold is precipitated over narrow temperature — (15–20°C) and restricted depth intervals, as shown on Figure 7-6.

Other processes resulting in mineral deposition include mixing of solutions and redox reactions. Mixing usually causes cooling as well as dilution, but mixing of fluids can also add components (for example H_2S , HCO_3^- , CO_3^{2-}) and increase solute concentration that promotes precipitation. Redox reactions with attendant dissociation of some complexes can lead to deposition by recombinations of metals and ions. For example, mixing of deep, near-neutral, chloride waters with near-surface, steam-heated acid sulphate waters is particularly effective in depositing gold by oxidation and acidification. Oxidation of the fluids preferentially partitions the reduced components (for example H_2S , CH_4 , H_2) into the vapour phase during boiling more rapidly than SO_4 , SO_2 , CO_2 . Consumption of oxygen decreases fO_2 and frees H^+ which lowers pH and reacts with S^{2-} , HS^- and HSO_4^- . This decreases the stability of, first, base metal complexes and then gold complexes causing precipitation.

Fluid-wall rock reactions that are particularly important for mesothermal deposits include *hydrolysis* (H^+ and OH^-) reactions which decrease or increase pH, and *hydration* reactions (H_2O consumption) that lead to buffering of solutions by mineral reaction equilibria. Gold precipitation can also result from iron sulphidation reactions (Fe to FeS_2) that reduce sulphur activity and from reduction of hydrothermal fluid by sulphide or graphite-rich rocks ($Au(HS)_2^- + H^+ + 0.5H_2 = Au^0 + 2H_2S_{gas}$). In addition some rocks, notably mafic and ultramafic, can act as chemical 'sinks' that consume components from the solution, mainly CO_2 , to form Fe-Mg-Ca carbonate minerals.

SUMMARY

The many inter-related, geologically constrained processes outlined above, act together and cause mineral deposition by:

- Changing mineral solubilities,
- Affecting association and dissociation of aqueous metal-bearing complexes thereby changing their stabilities in the hydrothermal solution,
- Promoting hydrolysis reactions which influence the availability of certain ions, notably $(HS)^-$ and Cl^- ,
- Controlling redox reactions, a function of oxygen fugacity (fO_2) and oxidation potential (Eh), which determine the relative amounts of the various ionic species critical for gold and other metal transport — mainly SO_4 , $(HS)^-$ and H_2S .

CORDILLERAN MESOTHERMAL GOLD DEPOSITS

GEODYNAMIC SETTING AND GENETIC MODELS

Mesothermal deposits are a distinct class of gold deposit (see Table 7-2) that is characterized by their geological and, more specifically, their 'geodynamic' setting in a continental margin, arc-continent, and rarely, a compressed back-arc continental margin collisional plate tectonic environment. Mineralization postdates metamorphism which peaks some time after orogenic crustal thickening. The deposits occur most commonly in shear zones within or adjacent to major terrane-boundary fault zones that display strike-slip motion. The auriferous quartz veins form large, vertically continuous quartz vein systems. The veins have enveloping carbonate alteration zones and contain only small amounts of ore and other sulphide minerals. Mineralization takes place under essentially isothermal conditions from deeply circulating, chemically evolved hydrothermal solutions that undergo decompression during regional structural disruptions.

Recent discussions of mesothermal type 'greenstone gold' deposits are found in the 1990 *NUNA* Conference volume, Robert, Sheahan and Green, Editors (1990). The conference reviewed: Tectonic and structural evolution of greenstone terranes;

structural setting and controls of gold deposits; fluid generation, fluid circulation and deformation; fluid and solute sources and models; P-T environments of gold deposition; nature and composition of auriferous fluids; wallrock alteration; and genetic models. Another especially notable discussion about the role of fluids in syntectonic mass transport and localisation of metamorphic vein-type ore deposits is by Cox *et al.* (1987).

A consensus according to Kerrich (1989b) is "that the first order (regional) control on the distribution of mesothermal precious metal deposits is structural, specifically in shear zones characterized by transitional behavior between brittle and ductile rheology". At district and deposit scale, mineral deposits are located in second and third-order structures such as subsidiary faults, cross-faults or splays off the large, predominantly strike-slip regional faults. Mineralization takes place when and where seismic or aseismic structural events promote fluid (H_2O , CO_2 , CH_4 and H_2S) immiscibility by pressure release (Guha *et al.*, 1991) and the evolved hydrothermal solutions encounter chemically reactive rocks. Favourable lithologies in the prevalent oceanic assemblages in which wallrock reactions leading to gold deposition take place produce carbonate-altered iron-rich, pyritized rocks in which carbon dioxide and sulphur are consumed (Bohlke, 1989), and graphitic rocks in which fluid reduction and sulphidation takes place.

The genetic models proposed and described by a multitude of authors are outlined and discussed by Kerrich, (1989b), pages 124-128, and Kerrich (1990). The main genetic models include: metamorphic dehydration, mantle CO_2 -granulitization, metamorphic replacement, lateral diffusion, meteoric water, syngenetic-exhalative, orthomagmatic fluid evolution from oxidized felsic magmas, tonalitic magmas and gold-rich lamprophyric source rocks. According to Kerrich, all the listed models have some deficiencies and conflict in some way with geochemical data and geological observations. But virtually every model has adherents and proponents with a deposit somewhere to support their case.

The three currently favoured hydrothermal models for mesothermal deposits in the Cordillera and other Phanerozoic regions (Nesbitt, 1991), as well as Archean greenstone terranes (Colvine *et al.*, 1984, 1988; Kerrich, 1989c; and Groves and Foster, 1991) are:

- **Meteoric model** — the hydrothermal solution is meteoric (surface) water that has been deeply circulated through permeable fracture systems. At depth, fluids leach gold and other vein constituents from the rocks through which they pass and then rise buoyantly along the ore-hosting structures after they become heated. This mechanism has been widely advocated by Nesbitt and co-workers, see Figure 7-7.

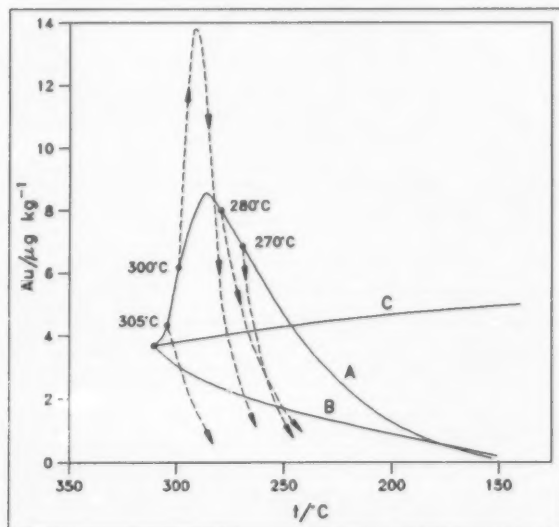


Figure 7-6. The effect of boiling on the solubility of gold as $Au(HS)_2$ in Rotokawa deep geothermal fluid. Curve A shows adiabatic closed-system boiling; curve B refers to conductive cooling; curve C shows the initial increase in gold concentration due to steam loss. Dashed lines represent open system boiling at indicated temperatures following adiabatic, closed system boiling to that point (curve a), from Seward (1991).

- **Metamorphic model** with two proposed variants:
1) Fluids are generated by prograde metamorphism of upper crustal rocks commonly during subduction, as described in the Juneau gold belt by Goldfarb *et al.* (1988, 1989, 1991) (see Figure 7-8) and the California Mother Lode deposits by Landefeld (1988), (see Figure 7-9). 2) Granulite-facies metamorphism (and dehydration) is caused by influx of mantle-derived magmas and carbon dioxide-rich fluid. Hodgson and Hamilton (1989) have proposed that Archean greenstone belt mineralization is related to deep crustal and mantle metamorphic-anatectic processes caused by thermal equilibration and uplift following arc-continent collisions.
- **Magmatic (or 'orthomagmatic') model** — the traditional view summarized by Burrows and Spooner (1989) that fluids are totally or in part derived from the devolatilization of cooling magmas, commonly minor felsic intrusions or lamprophyres. Note that the amount and identity of magmatic components in the hydrothermal flu-

ids is a matter of conjecture and long-standing dispute.

A model of deep convection (12 to 15 km) and chemical evolution of meteoric water in the brittle crust has been advanced by Nesbitt and co-workers, mainly on the basis of fluid inclusion stable isotope interpretations (see Figure 7-7 and Nesbitt *et al.*, 1986; Nesbitt and Muehlenbachs, 1989). They propose that structurally-controlled, deeply circulating, buoyant, meteoric-source hydrothermal fluids form gold-quartz veins at depth and related mineralization with antimony and mercury in shallower or more distal, cooler sites (Nesbitt *et al.*, 1989). The model proposes that groundwater penetrates fractured rocks in the brittle, upper crustal regime and flows by convection. Depth of fluid flow is limited by the brittle-ductile transition below which permeability is significantly diminished. The fluids evolve chemically and isotopically at low water to rock ratios by interaction and re-equilibration with wallrocks. Vein constituents are leached and transported upward in a thermal convection cell from hostrocks that are

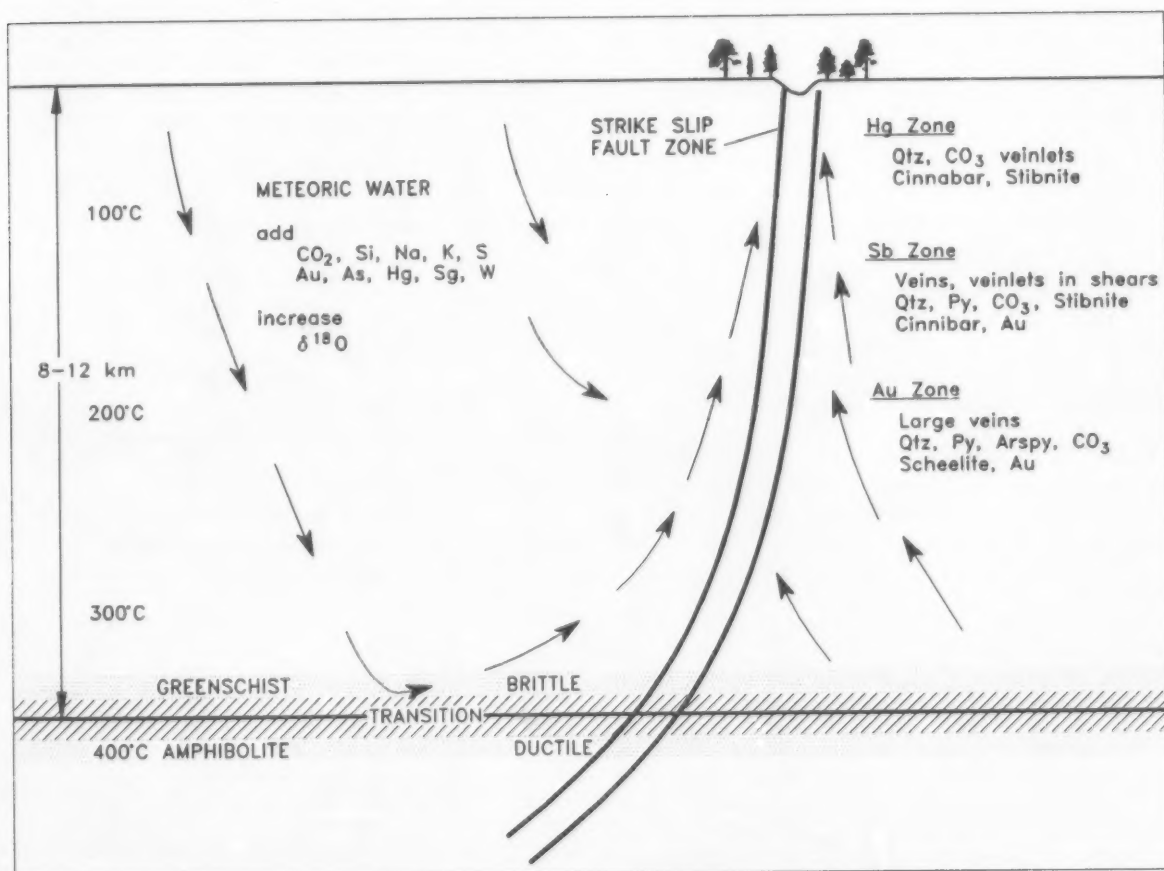


Figure 7-7. Mesothermal model proposed by Nesbitt and Muehlenbachs (1989) showing convection of meteoric water, fluid re-equilibration, a buoyant ascending fluid entrainment and gold, antimony and mercury mineralization.

undergoing hydrolysis and possibly dehydration. The precipitating mechanism is mainly phase separation under hydrostatic pressure conditions during fluid ascent or changes from lithostatic to hydrostatic conditions by structurally induced depressurization. This causes immiscible gas effervescence that leads to loss of reduced components (mainly sulphur) to the vapour phase. Nesbitt and Muehlenbachs state that the typical sequence — early quartz, carbonate, iron and arsenic sulphides followed by late gold mineralization, takes place at depths of around 10 kilometres and temperature around 300°C. The remaining fluid rises, cools and deposits antimony at shallower depths at around 100°C and mercury in even cooler, near-surface cinnabar deposits. Note that this model envisions antimony and mercury to be deposited from ascending, low temperature hydrothermal solutions and boiling to dryness, as discussed by Spycher and Reed (1989), which is probably impossible in this geological setting, is not necessary.

The model of Nesbitt and coworkers is based largely on the isotopic signature of bulk fluid inclu-

sion analyses. Clearly there is a coupling of fluid flow and deformation during the genesis of mesothermal veins (Cox *et al.*, 1987, 1990; Sibson, 1990) but post-ore deformation will introduce additional (secondary and other) fluids into the vein structures as well. The presence of multiple generations of fluids in vein minerals is evident from detailed studies a number of mesothermal deposits as recently documented by Taylor *et al.* (1991). Therefore any model based on bulk fluid inclusion analyses is probably too simplistic to adequately explain the complex mineralization and post mineralization veins histories.

In contrast to Nesbitt and co-workers, Goldfarb *et al.* (1991) have concluded from their studies in the Juneau gold belt, that gold mineralizing hydrothermal solutions have a deep crustal source, and are most likely of metamorphic origin. Although quartz veins are found in rocks of all metamorphic grades, gold occurs only in veins from upper prehnite to lower amphibole facies rocks, virtually all from only the northern 200 kilometres of the Coast megaligneament. The southern 500 kilometres of the mega-

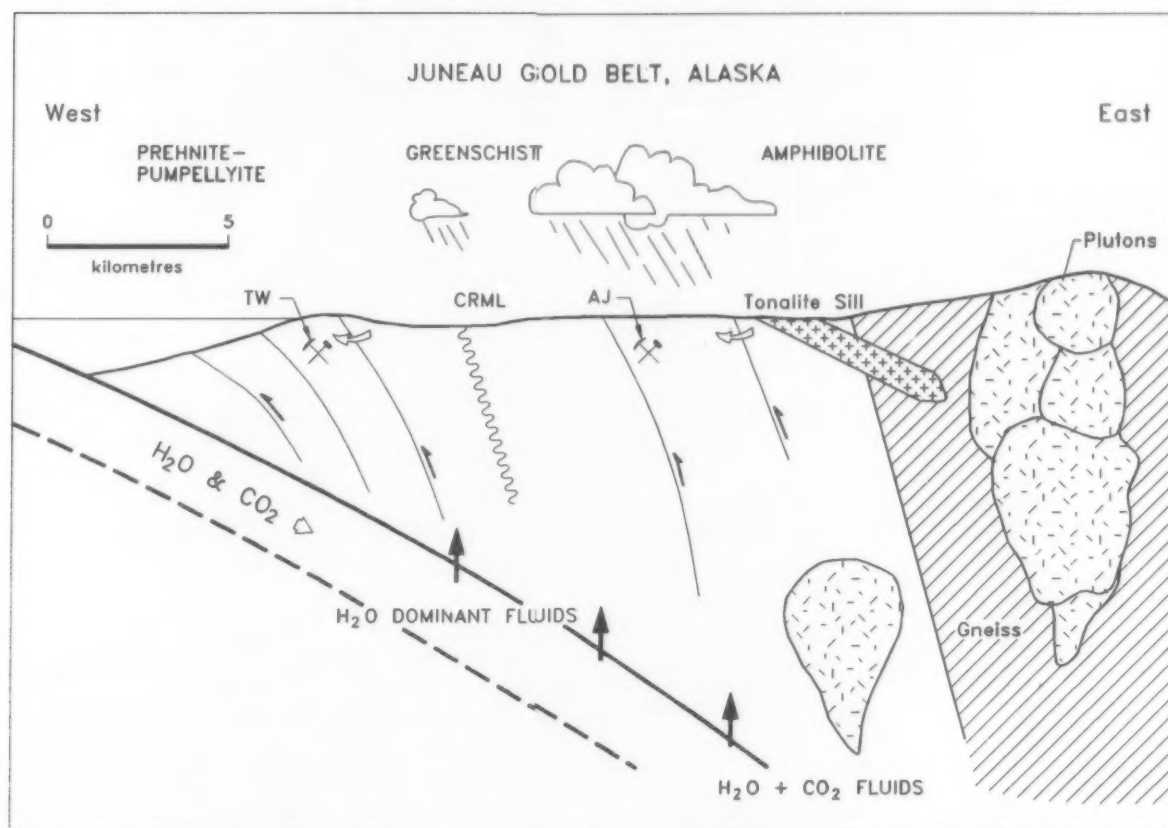


Figure 7-8. Generation of ore fluids in the Juneau gold belt by prograde metamorphic devolatilization during subduction-related crustal underplating. Ore fluids with contrasting CO_2 content occur east and west of the Coast Range megaligneament (CRML), from Goldfarb *et al.* (1988, 1989). Major mines shown for reference are (TW) Treadwell and (AJ) Alaska Juneau.

lineament in higher grade metamorphic rocks has proven to be unproductive. The ore fluids are derived from devolatilizing (by dehydration and decarbonization) subducted crust during Tertiary prograde metamorphism of mainly pelitic rocks. They conclude from their stable isotope studies that meteoric water was *not* a significant component within the ore fluids but was introduced later and overprints older rocks and mineral deposits. They describe two distinct types of hydrothermal fluid. One type, a predominantly H₂O-rich fluid with 3 to 10 mole per cent carbon dioxide was trapped in fluid inclusions as a homogeneous single fluid phase. It occurs to the west of the Coast Range megalineament. The other type, found to the east of the megalineament, is an unmixed carbon dioxide-rich aqueous solution with between 40 and 60 mole per cent carbon dioxide. They propose that the contrast in the two fluids is a consequence of their different depths of origin in the subducting plate — the western, aqueous fluids evolved from low to medium-grade greenschist sources; the eastern, gas-rich fluids are derived from deeper, more advanced metamorphic zones near the greenschist-amphibolite boundary. Both types of fluid caused gold mineralization at mid crustal levels in predominantly Late Jurassic to mid-Cretaceous metasedimentary sequences following peak metamorphic conditions. Indeed, all the 6.7 million ounce (208 tonne) gold production has come from deposits within 5 kilometres, both east and west, of the megalineament and about 20 kilometres west of the Coast batholith (Goldfarb *et al.*, 1989).

The mineralizing conditions determined by Goldfarb and co-workers are typically mesothermal. Fluids were dilute (<5% NaCl-equivalent), temperature was around 250°C and depth of mineralization was at least 5 kilometres. An interesting comment by Goldfarb is that since some fluids did not unmix and evolve gas, fluid-wallrock reactions must have been an important depositional mechanism. This is a contentious interpretation and will likely need to be revised as better information becomes available. A similar interpretation about wallrock reactions is made by Leitch *et al.* (1991b) for the Bridge River district, British Columbia. Interestingly, whereas Goldfarb *et al.* (1991) state that gold transport was by bisulphide complexes, Leitch *et al.* (1991b) consider chloride complexing as the gold-transporting agents (possibly due to higher fluid temperatures of around 350°C). However, both groups of authors regard fluid-wallrock reactions involving production of pyrite by sulphidation and redox reactions (ore fluid sulphur oxidation with concurrent aurous ion reduction) as the causes of gold precipitation.

TIMING AND SEQUENCE OF MINERALIZING EVENTS

The onset of hydrothermal fluid activity and resulting mineralization appears to take place some time after culmination of prograde metamorphism. This

time delay has been variably estimated to range from just a million up to 40 million years. The genetic role of magmatism in mineralization is more obscure. Consider the following sequence of events described by Goldfarb *et al.* (1988) in the Juneau gold belt and typical of mesothermal gold districts: convergent accretion with underplating of the continental margin takes place from 70–50 Ma. Metamorphism is initiated around 77 Ma and continues until 55 Ma. During this interval, sodic magmatism, mainly emplacement of tonalite sills, takes place from 69 to 64 Ma. Rapid uplift occurs and mineralization over a very brief interval from 55.5 to 55.1 Ma is followed by extensive calcalkaline magmatism starting around 50 Ma. The remarkably short duration of mineralization and its intimate relationship with specific metamorphic rocks adjacent to a major crustal structure, implies a common thermal setting for the gold deposits within a tectonic event.

A model for the genesis of ore fluids that discusses at length the role of Cordilleran magmatism is provided by Landefeld (1988) for the Mother Lode district in the foothills metamorphic belt, west of the large Sierra Nevada batholith. The presence of similar and contemporaneous mineralization in a number of gold camps over a 230 kilometre distance attests to large-scale structural and tectonic ore controls. Landefeld favours fluid generation by dehydration during thermal re-equilibration of the accretionary prism. Bohlke and Kistler (1986) concluded that the fluids were locally derived, complexly evolved and *not* (solely) seawater, meteoric water nor magmatic water. The role of magmatism in the origin of the deposits is summarized by Landefeld. The following discussion paraphrases Landefeld's Figure 4, page 54 (Landefeld, 1988) and complements Figure 7-9, taken without any changes from her discussion. The figure shows the following gold mineralizing sequence during convergent continent-margin compressional tectonism resulting from oblique subduction:

- A. 150 Ma — The foothills accretionary prism is deformed during subduction. Minor partial melting and synorogenic intrusion begin.
- B. 140 Ma — Subduction steps westward (outboard), isotherms rise in the accretionary complex as the wet, cold sediments become warmer and start to expel water. When P_{fluid} exceeds $P_{\text{lithostatic}}$ or fracturing creates permeability through to the surface and hydrostatic pressure conditions ensue, carbon dioxide-rich fluid separates and migrates into fault zones. Fluid migration is initiated by faulting but the presence of pressurized fluids probably promotes additional episodic faulting and hydraulic fracturing (Sibson *et al.*, 1988). The depressurization should predictably cause mineralization and this appears to be the case. Bohlke and Kistler (1986) report mineralizing ages in the gold belt from 140 to 110 Ma, with mean and median ages of mineralization between 120 and 115 Ma.

- **C. 130 Ma** — Large-scale partial melting begins, promoted by the presence of residual fluids, more saline than seawater, left after 'boiling' off the carbon dioxide-rich fluids. Large-scale batholithic emplacements begin along the actively uplifted and faulted zones. The main 120 to 90 Ma batholiths consist of dry magmas that further dehydrate already devolatilized rocks. Thus, no appreciable hydrothermal activity accompanies late magmatic emplacements. Uplift in the region was rapid; clastic detritus containing mineralized vein material was deposited in the adjoining forearc basin by 113 to 110 Ma.

The conclusion would, therefore, seem to be: Magma is generated within the same tectonic cycle and from the same depth within the crust as are hydrothermal fluids, but not at the same time. Magma emplacement is facilitated by the same structures that allow earlier passage of hydrothermal fluids, but the relationship between intrusions and hydrothermal fluids is spatial, not necessarily genetic.

MAJOR BRITISH COLUMBIA MESOTHERMAL DEPOSITS

The Bridge River camp is British Columbia's foremost historic gold producer. Most of the gold produc-

tion has been from mesothermal veins at the Bralorne-Pioneer and Wayside deposits. However, the district also includes a wide variety of other types and ages of metallic deposits.

- **Bridge River Camp** — Bralorne, Pioneer, Congress, Wayside, Reliance, Minto — MINFILE 092JNE001, 2, 7, 4, 29, 30, 33:

The important mesothermal deposits are within the Bralorne fault zone and are hosted by diorite, soda granite and greenstone. Early studies by Cairnes (1937), and others, summarized by Barr (1980) proposed that the mesothermal vein gold-quartz deposits were related to a number of (old) intrusive bodies — the Bralorne intrusions and/or albitite and porphyry dikes. Structural controls of the deposits were emphasized by Joubin (1948). Studies by Leitch and Godwin (1988), Leitch (1990) and Leitch *et al.* (1989, 1991a, 1991b), mainly concerned with mineralizing processes, but also including extensive radiometric dating, have documented that Bralorne mineralization occurred between 91 to 85 Ma. These investigations, as well as studies of the regional geological setting of mineralization by Schiarizza *et al.* (1990) and Schiarizza and Gaba (in preparation), document that the mesothermal gold-quartz veins are the oldest metal deposits in the camp and they occupy some of the earliest-formed structures in the district. The veins are typically hosted by Early Permian intrusions and greenstone in tectonic blocks within the Bralorne fault zone. This is an oblique, northwesterly-trending, structurally complex, reverse-sinistral fault zone that was active during Late Cretaceous regional transpression (Schiarizza *et al.*, 1990). The ages of the veins are between 91 and 85 Ma as constrained by crosscutting dikes. These dikes, as apophyses of the Coast Plutonic Complex, have historically been proposed to be the heat source for the veins. However, the work by Leitch and co-workers points to a large, probably magmatically-derived hydrothermal fluid reservoir developed deep within the roots of the extensive high-angle fault system as the source of the mineralizing solutions. They describe a progression of fluid compositions with typical, early-mineralizing 'primary' fluid having high temperature (350°C), significant carbon dioxide and methane content ($x_{CO_2} + x_{CH_4} = 0.15$), fluid isotopic composition calculated to be $\delta^{18}O = +13$ per mil, salinity around three weight per cent NaCl-equivalent and pressures of between 100 to 175 megapascals (6 to 10 kilometre depths). Later fluids, presumably diluted by meteoric water, were cooler, dilute, contain little carbon dioxide and no measurable methane. They were involved in mineralization at depths of 2 to 6 kilometres during late hydrothermal stages, evidently after rapid uplift of the region. The high-angle reverse faults acted as fluid-pressure (and tectonically?) activated valves (Sibson *et al.*, 1988) on pressurized fluid reservoirs. Episodic pressure releases caused mineral deposition.

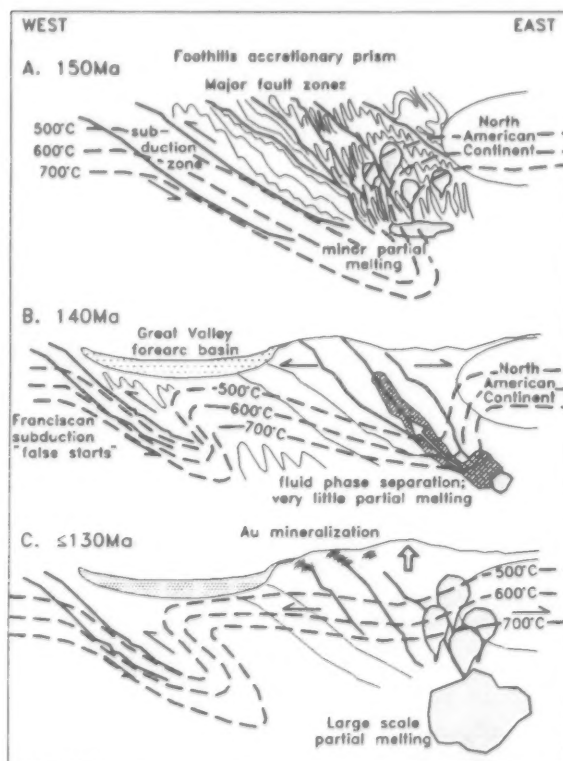


Figure 7-9. Model for the genesis of Mother Lode ore fluids during convergent plate tectonism, from Landefeld (1988); see text for explanation.

The distribution of gold, silver, arsenic, antimony, mercury, tungsten and molybdenum in various types of deposits was interpreted by Woodsworth *et al.* (1977) to represent a district-wide zoning of metals. The zoning is interpreted to be related to a district-wide thermal gradient that decreased away from the Coast Intrusions on the west. They support the notion of a northeasterly-migrating magmatic (and mineralizing) front related to the Coast Plutonic Complex thermal aureole. The possibility of two mineralizing centres is outlined in their discussions. On the other hand, Schiarizza and co-workers on the basis of work in the Bridge River-Taseko Lakes area during 1986 to 1990 (Schiarizza *et al.*, 1990; Schiarizza and Gaba, in preparation), draw attention to the metallogenic evolution of the district through a sequence of mineralizations in a series of changing, complex structural and magmatic settings. They consider that mineralization coincides with several pulses of igneous activity and varying structural regimes that changed from transpressive to transtensional from latest Early Cretaceous to mid-Tertiary time.

The following discussion outlines the conclusions by Schiarizza and Gaba (in preparation) about mineralization in the Taseko Lakes-Bridge River district. The wide variety of metallic lode deposits spatially and temporally related to igneous rocks and/or faults includes: mesothermal gold-quartz veins, porphyry copper and molybdenum, auriferous polymetallic veins, scheelite-stibnite veins, auriferous stibnite veins, disseminated (epithermal) gold and cinnabar-bearing veins and disseminations. The relationship between the various types of metal deposits, their ages, hostrocks and structural sites is summarized in Table 7-5 and illustrated on Figure 7-10.

Porphyry copper and molybdenum prospects are associated with 86 million-year-old intrusive rocks of the Coast Plutonic Complex, a number of similar-age and 64 Ma plutonic rocks to the east, and 58 Ma intrusions at Poison Mountain, two kilometres east of the Yalakom fault. Polymetallic veins, commonly rich in silver or copper, have formed peripherally to some of the porphyry systems.

Auriferous polymetallic and stibnite veins associated with 69 to 67 Ma dikes occur in the Minto and Congress mine area. The deepest levels of the Congress mine contained significant gold associated with diffuse, fine-grained pyrite-arsenopyrite-sphalerite replacements adjacent to the main stibnite-hosting shear zone. The upper parts of the vein system contained predominantly coarse stibnite in discrete shear-hosted veins and also small amounts of cinnabar. Overall, the Congress mine exhibits a transition from the upper part of an auriferous polymetallic vein occurrence through to a higher-level epithermal-type stibnite-cinnabar deposit.

The youngest cinnabar and scheelite-stibnite veins are thought to be Eocene in age. They are

associated with northwest-trending, strike-slip trans-tensional faults such as the Yalakom and Relay Creek-Marshall Creek faults. The mineralization occurs mainly in serpentinite within fault zones that had been hydrothermally altered to quartz-carbonate-mariposite (listwanite) assemblages. Abundant small porphyry bodies in the area might be contemporaneous with, and related to, mineralization.

The youngest hydrothermal activity noted in the district appears to be 27 Ma epithermal-type mineralization at Big Sheep Mountain. Disseminated gold associated with rare tetrahedrite is found in vuggy, limonitic quartz seams in argillically altered quartz-porphyrific rhyolite that is emplaced within, or overlies, a feldspar-porphyry pluton.

As summarized by Schiarizza and Gaba (in preparation): "Overall, the regional metallogenic evolution of the Taseko Lakes-Bridge River area is complex. Metallic mineral deposits apparently formed over a protracted interval during (earliest) Late Cretaceous to mid-Tertiary time, coincident with several pulses of igneous activity within an evolving structural regime that generated transpressional, and later, transtensional structures."

Other major mesothermal deposits noted in Table 7-3 are briefly described below. The descriptions are extracted mainly from MINFILE data files, augmented in some cases from various other Ministry files, Barr (1980) or other published sources, as noted:

■ **Rossland Camp** — LeRoi, Centre Star; MINFILE 082FSW093, 94:

The Rossland area is underlain largely by Early Jurassic volcanic rocks of the Elise Formation (Rossland Group). They overlie Paleozoic metasedimentary rocks of the Mount Roberts Formation and are locally in apparent fault contact with Carboniferous rocks. Four igneous suites are recognized. The Rossland monzonite centered near the gold camp is an Early Jurassic pluton that is thought to be cogenetic with the Rossland Group (Höy *et al.*, 1992). It trends east-westerly along a prominent structural break that marks a zone of syndepositional growth faults and late thrust faults. This structure also contains a number of ultramafic bodies and hosts the main mineralized vein systems. Also important is an augite porphyry intrusion known as the Rossland sill that hosts a number of the principal orebodies of the camp. Other intrusive suite comprise the middle to Late Jurassic Trail pluton, alkaline middle Eocene Coryell intrusions and the middle Eocene Sheppard stocks and dikes.

The Rossland gold-copper veins are dominantly composed of pyrrhotite with chalcopyrite in a gangue of altered rock with minor lenses of quartz and calcite. The veins occur in three main belts — the Main, North and South. The Main veins follow a continuous, well-defined 070 degree trending fracture system over a distance of about one kilometre.

TABLE 7-5

Metallogenic Summary of Bridge River-Taseko Lakes Area

DEPOSIT TYPE (Map symbols Figure 7-10)	AGE	LOCATION OR HOST LITHOLOGY
Mesothermal veins (MV)	Late Cretaceous 91-85 Ma	Bralorne-Pioneer, Wayside, (Elizabeth?)
Porphyry Cu and associated polymetallic veins (p1PV)	Late Cretaceous 86 Ma	Veins adjacent to Coast Plutonic Complex
Porphyry Cu prospects (p2)	Late Cretaceous 86? Ma	Upper Relay Creek intrusions
Polymetallic-stibnite veins (PSV)	Late Cretaceous 69-67 Ma	Minto-Congress area
Polymetallic veins (PV2)	Paleocene 64-57 Ma	Eldorado Pluton
Porphyry Cu (p3)	Paleocene/Eocene 58 Ma	Poison Mountain (east of Yalakom fault)
Porphyry Cu-Mo, Mo (p4) and related polymetallic veins (p4PV)	Eocene 44 Ma	Loma Lake pluton; veins adjacent to Mission Ridge Pluton
Scheelite-stibnite-cinnabar (SSC)	Eocene	Yalakom, Relay Creek faults
Epithermal gold (epAu)	Oligocene 27 Ma (alteration)	Big Sheep Mountain intrusive-extrusive complex

Summary data from R.G. Gaba, written communication, May 1991, (Schiarrizza and Gaba, in preparation).

More than 98 per cent of the ore shipped from the Rossland camp was produced from these veins, of which over 80 per cent came from deposits in a central zone between two large north-trending lamprophyre dikes. The Main vein system consists of a series of steeply northward dipping, commonly en echelon veins that are hosted mainly by the Rossland sill or Rossland monzonite. Elsewhere they crosscut bedding but appear to be cut by the late north-trending faults and associated dikes. The North belt is a zone of discontinuous veins that strike easterly and dip northward at 60 to 70 degrees. The largest veins are up to 2 metres in width and occur in the Rossland sill. In the South belt the principal veins trend 110 degrees and dip steeply either to the north or south. They are hosted by siltstone, lapilli tuff and augite porphyry of the Elise Formation several hundred metres to the south of the Rossland monzonite. In addition to the typical gold-copper mineralization, the veins in the South belt also contain sphalerite, galena, arsenopyrite and boulangerite.

The LeRoi deposit, part of the Main vein system, consisted of a series of narrow ore shoots with short strike-length but good down-dip persistence. The veins were formed along a main fissure or fault zone by fracture fillings of pyrrhotite and chalcopyrite with some quartz and calcite gangue. Actinolite, pyrite and garnet are associated with some of the pyrrhotite and chalcopyrite mineralization. Disseminated pyrite occurs in the wallrocks. The deposit was mined over a vertical extent of 600 metres. Refer to Fyles (1984).

■ **Cariboo-Barkerville Camp** — Island Mountain and Aurum, Mosquito Creek, Cariboo Gold Quartz — MINFILE 093H 006, 10, 19:

Gold has been produced from quartz-pyrite veins and from pyritic lenses in limestone, the so-called 'replacement orebodies'. Typical grade of veins was about 12 grams per tonne and that of the pyritic orebodies on the order of 20 grams per tonne gold. The ores are hosted by folded and regionally metamorphosed metasedimentary rocks of the Downey succession of the Hadrynian to Lower Paleozoic Snowshoe Group. The hostrock sequence consists of quartzite, conglomerate, siltstone, slate, phyllite, marble, limestone, dolomite, amphibolite and possibly metatuffs.

Quartz-pyrite veins occur in extensively fractured fine-grained sedimentary rocks in a clastic unit referred to as the Rainbow Member. The ore-bearing veins contain up to 25 per cent pyrite and small amounts of galena, sphalerite, arsenopyrite, scheelite and cosalite. Four types of veins have been described according to their orientations (Barr, 1980): 1. Transverse veins that strike N30-55°E and dip 70 to 90 degrees southeast. Although small, the veins are numerous and provided from 60 to 75 per cent of the vein ore; 2. Diagonal veins up to 1.5 metres in width with average strike lengths of 46 metres, strike N70°E to east and dip steeply to the south; 3. Strike veins are the most continuous veins. One of the veins developed over a vertical distance of 275 metres is 790 metres long with widths up to

13 metres. However, these veins are commonly barren or are sparsely mineralized and only one was mined; 4. Northerly trending veins.

Replacement ores which account for over 25 per cent of milled ore at the Island Mountain mine but less than 10 per cent at Cariboo Gold Quartz mine consist largely of pyrite with minor arsenopyrite. The replacement bodies occur at the contacts and within certain limestone beds referred to as the Baker Member. They occur throughout a vertical interval of about 915 metres. Ore bodies are located in the crests or noses of minor folds and, less frequently, fold troughs. The replacement ores form pencil-shaped bodies from 2 to 8 square metres in cross section and up to 600 metres in length. Some also occurs as tabular orebodies with maximum dimensions of about 50 metres. The replacement ores are associated with extensive carbonate and sericite wallrock alteration. Refer to summaries of older descriptions of deposits by Barr (1980).

■ **Sheep Creek** — Queen, Reno, Kootenay Belle, Gold Belt, Nugget, Vancouver — MINFILE 082FSW048, 36, 46, 44, 40, 49:

The Sheep Creek camp lies along the eastern boundary of the Kootenay Arc in the southern Omineca crystalline belt. The area is underlain by a thick succession of complexly folded and faulted late Proterozoic and early Paleozoic sedimentary rocks of mainly the Quartzite Range, Reno, Laib and Active formations. The Windermere Supergroup is found to the east of the camp; Mesozoic eugeosynclinal rocks of the Rossland Formation occur to the west of the camp. The region is intruded by numerous granite, quartz monzonite, quartz porphyry sill and dike and lamprophyre bodies.

Four sets of faults are recognized but only the north-easterly-trending dextral strike-slip faults have significant associated mineralization. Quartz veins, a few centimetres to more than two metres in width, display extensive vertical and lateral continuity and are the only economically significant mineralization. The veins are spaced about 150 to 700 metres apart along a 6 kilometre belt that contains between 20 to 30 veins. Gold occurs as small, isolated particles generally <30 microns in size within the veins and is associated with sphalerite, galena and pyrite. Mineralization is confined to those veins which are bounded on one or both sides by quartzite (Mathews, 1953).

■ **Snip Mine** — MINFILE 104B 250:

The workings are developed on a 0.5 to 15 metre wide shear-hosted quartz-carbonate-sulphide vein (the Twin zone) within massive feldspathic wackes and siltstones of probable Early Jurassic age. The Twin zone is made up of two ore bands separated by a thin rib of waste rock, mainly a post-ore, fine-grained basic dike. The zone occupies a 120 degree-trending structure that dips from 30 to 90 degrees northward. The deposit has been traced down dip for

about 250 metres and has a strike length of one kilometre. The ore zone is offset by minor faults and displays an extensive array of right lateral tension gashes. A number of feldspar porphyry intrusions with weak porphyry copper-gold mineralization occur on the property and are considered to be genetically related to the gold mineralization.

The ore shows little variation over the vertical range tested and consists predominantly of 1 centimetre to 1-metre-wide bands of alternating massive calcite, disseminated abundant to massive pyrite, pyrrhotite, biotite and quartz. The sulphides commonly form streaky bands, locally accompanied by brecciated wallrocks or pyritic fault gouge. Three main ore types are: (1) quartz-carbonate veins, containing minor to accessory pyrite bands; (2) crackled quartz with green mica and disseminated sulphides; and (3) massive sulphide chalcopyrite, sphalerite, galena, molybdenite and arsenopyrite. Minor amounts of bismuth and telluride minerals have been reported in company reports. Native gold occurs at the margins of pyrite, arsenopyrite and telluride grains and to only a minor degree, in gangue minerals. Narrow parts of the ore zone consist of one sulphide layer while thicker sections show repetitive banding of the various ore types. These thicker sections also contain interbands of biotite-carbonate-K-feldspar altered feldspathic wacke. A moderate to strongly developed foliation is evident and is accentuated by biotite (chlorite) rich bands. High grade gold vein assay boundaries are generally sharp although minor amounts of gold are present in the immediate wallrocks.

■ **Frasergold** — MINFILE 093A 150:

This prospect on McKay Creek in the headwaters of the Horsefly River system is underlain by Late Triassic black metasedimentary black clastic rocks locally referred to as the Quesnel River Group (Nicola Group equivalent). Gold mineralization is vein hosted but shows some preference for certain of the metasedimentary units. Mineralization is localized along the moderately southwest-dipping northern limb of the Eureka Peak syncline and concentrated near the basal contact of a distinctive porphyroblastic siderite-ankerite-chloritoid-bearing phyllite with underlying graphitic banded phyllites. A penetrative slaty to phyllitic foliation is developed axial planar to tight isoclinal folds. The veins are generally parallel to foliation and subparallel to bedding.

Gold occurs in quartz and quartz carbonate veins ranging from 2 to 20 centimetres in thickness and extending 1 to 10 metres along strike. The veins form discontinuous lenses, rolls and saddle reefs. Quartz occurs usually as massive, white intergrowths with rare small vugs, minor pyrite and pyrrhotite and rare chalcopyrite, sphalerite and galena grains. The formation of the veins is synchronous with regional metamorphism and deformation although some of the auriferous quartz is remobilized into younger minor fold hinges and crenulation cleavage. The



Plate 7-1. Cassiar quartz vein types. (A) Greenstone-hosted, steeply dipping (Jennie) vein with spalled blocks of wallrock within the vein; (B) Argillite-hosted, flat, graphite-ribboned (Vollaugh) vein at volcanic-sediment contact. The vein exhibits a duplex structure created by movement along a gently dipping decollement plane marked by the straight band in centre of vein. Late fault movement is related to north-south extension. Scale length is 25 centimetres. Photographs by Joanne Nelson.

development of the auriferous quartz veins is thought to be synchronous with Late Jurassic regional metamorphism and deformation. Deformed and undeformed veins occur on all scales along the limbs and within the hinge regions of folds.

A stratigraphic horizon of knotted black phyllite, about 200 metres thick, is geochemically anomalous for gold over a distance of 10 kilometres. All drill holes completed in this unit in 1987 intersected gold mineralization with 0.7 grams per tonne gold, or better, over 30 metres. Local zones ranged from 5 to 24 grams per tonne gold over 3 to 6 metre widths. Refer to Bloodgood (1990).

■ **Sulphurets Camp** — Brucejack Lake Zones — MINFILE 104B 189, 190, 193:

At least eighteen mineralized zones with a variety of mineralization ranging from porphyry copper-molybdenum-gold, quartz-molybdenum stockworks, disseminated and breccia-hosted gold, complicated to simple mesothermal to epithermal vein systems and quartz-alunite zones with native sulphur have been identified in a large intrusion-related alteration zone. Hostrocks are Early Jurassic andesitic volcanic and sedimentary rocks that have been intruded by a number of syenitic stocks. The setting might well exemplify a transitional environment in which both mesothermal and epithermal-type deposits are genetically related to intrusive activity.

The mesothermal(?) silver-gold mineralization with elevated arsenic and antimony content occurs in structurally controlled vein systems and stockworks in an area of intense sericitic alteration. The veins vary from single, centimetre-thick quartz-electrum veins to metre-wide silver-gold-base metal quartz-carbonate veins with up to 20 per cent sulphide minerals. Pyrite with sphalerite, tetrahedrite, galena, chalcopyrite, and pearceite, proustite, acanthite and native gold are present. Calcite forms late, large fracture fillings, locally with minor barite.

■ **Golden Bear Mine** — MINFILE 104K 079, 87, 88:

This deposit was discovered in 1981. It is the first to be exploited of a number of auriferous zones within a 10 kilometre-long hydrothermally altered regional structural break. The fault-fracture zone, called the Ophir Break, marks the north to northwesterly-trending faulted contact between Permian limestones and Triassic volcanics. The 3500 metre wide structural zone is marked by areas of intense fracturing, carbonaceous and siliceous siltstone, fault gouge and linear zones of quartz-iron carbonate-pyrite-fuchsite (listwanite) and quartz-dolomite alteration.

Three major deposits — the Bear Main, Fleece Bowl and Totem Silica crop out at about 1.5 kilometre intervals. They form as pod-like, silicified dolomitized limestone masses in contact with brecciated and altered volcanic rocks. The auriferous zones are up to 10 metres in width and are at least 200 metres

deep. Mineralization consist of pyrite with arsenopyrite, native gold, pyrrhotite, chalcopyrite, stibnite, tetrahedrite and hessite. Pyrite occurs as late-stage veinlets, breccia matrix, rims on silicified limestone breccia fragments and as replaced laminations in altered tuffs. Alteration minerals include quartz, dolomite, pyrite, kaolinite, sericite/illite, and chlorite. Locally gypsum is present. Radiometric dating on sericite (Schroeter, 1987) suggests an Early to Middle Jurassic age of mineralization.

■ **Zeballos Camp** — Spud Valley, Privateer and other mines — MINFILE 092L 008, 9, 10, 11, 12, 13, 15, 16, 17, 19, 20:

A number of small quartz veins in a quartz diorite stock and to a lesser extent the surrounding hostrocks, were mined from 1933 to 1953. The Tertiary stock intrudes Jurassic volcanic rocks of the Bonanza Group and some limestones of the Late Triassic Quatsino Group.

The productive veins are generally less than 30 centimetres in width but they are continuous and display little lateral or vertical variation in widths or grades. They mostly strike N50 to 80°E and are found along the intrusive contact or close to it within the intrusive body. The quartz veins consist of granular white quartz intergrowths, commonly with open, vuggy comb structures and minor calcite. Locally they show evidence for late fracturing and recementing. Commonly the veins have narrow altered envelopes containing sericite. Sulphide minerals in the veins can form massive sulphide masses several centimetres in width but most commonly occur as scattered grains of pyrite, arsenopyrite, sphalerite, galena, chalcopyrite, possibly boulangerite and trace amounts of other ore minerals along with free gold.

■ **Cassiar District** — Erickson Gold, Taurus (Hanna), Cusac, Vollaug — MINFILE 104P029, 12, 70, 19:

Numerous auriferous quartz veins are found in a northly-trending 12 kilometre-long belt near the western part of the Sylvester Allochthon. This is an assemblage of Late Paleozoic to Early Triassic oceanic rocks, including small ultramafic bodies, that is tectonically emplaced onto Paleozoic platform rocks. It is intruded locally in the west by the Cassiar batholith and younger plutons. Auriferous mineralization occurs in volcanic rocks near the base of a Triassic sedimentary unit as steeply-dipping, granular, white quartz veins (Erickson, Taurus and Cusac). It also is found along volcanic-sedimentary contacts as flat-lying, ribboned, graphitic quartz veins and quartzose lenses (Vollaug) (Plate 7-1). Thrust faults commonly follow the volcanic-sedimentary lithologic contacts as well and these faults in some cases are mineralized with quartzose pyritic masses (Taurus).

Quartz vein systems at the Erickson (Jennie, Maura, Alison and Caitlin veins) and Cusac deposits

(Dino, Hot, Eileen veins) fill either sheared fault zones or extensional structures (Plate 7-1). Veins are commonly about a metre wide but can be up to 5 metres in width. They generally trend westerly and dip steeply either north or south. Ore shoots commonly form where the veins pass from competent to less competent lithologies close to the main volcanic-Triassic sedimentary unit contact. Mineralization consists of small grains of pyrite, tetrahedrite, chalcopyrite, sphalerite, arsenopyrite, covellite and gold. Veins commonly have 1 to 15 metre-thick alteration envelopes containing sericite, carbon, carbonate minerals and euhedral pyrite. Listwanite (quartz-carbonate-fuchsite) alteration is associated with a number of the better grade veins in fault structures.

At the Taurus mine (Cornucopia, Hanna property) near the northern end of the gold belt, a number of 0.5 to 2-metre-wide veins trending N 80°E in a succession of pillowed volcanic flows constitute the main ore sources. The quartz veins contain pyrite with minor tetrahedrite, sphalerite, chalcopyrite and arsenopyrite. Cores of veins and their marginal selvages contain visible gold. The sulphide minerals form bands 10 to 20 centimetres wide within the veins or along vein margins. The veins also contain some calcite, commonly exhibit graphitic banding and have 1 to 2-metre-wide carbonate alteration envelopes containing euhedral pyrite. At depth in the mine workings a shallow-dipping thrust fault with graphitic and chloritic margins appears to offset the main vein system. The fault zone is host to pyritic brecciated quartz, quartz veinlets and stockworks within the fault zone and pyritic replacements in its hanging wall. The replacements consist of about 3-metre-thick bodies of massive to semimassive, fine-grained pyrite. They have been reported (Gunning, 1987) to contain, on average, 8.53 grams per tonne gold over the average 3.1 metre width of the zone.

The Vollaug vein was extensively first explored during the 1930s. It is prominently exposed on Table Mountain over a 2 kilometre strike length as a semi-continuous, shallow to moderately northward-dipping, graphitic, ribboned quartz vein or series of quartz lenses up to 3 metres in thickness. The mineralization forms along the contact between Triassic argillite and the underlying greenstones. This is probably a major decollement along which major thrust fault movements have taken place. A number of north-trending faults offset the vein and have displaced the western parts of it towards the north. The ribboned, graphitic quartz contains free gold and pyrite, tetrahedrite, chalcopyrite with minor galena and sphalerite.

The age of the auriferous quartz vein systems is determined (Sketchley *et al.*, 1986) to be around 130 Ma (Early Cretaceous). A tectonic/structural origin for these vein systems is generally proposed. An alternative explanation for the Cassiar district

vein systems is offered by Nelson (1990). She suggests that mineralization is related to a buried intrusion that underlies the Cassiar gold belt. Refer to Nelson and Bradford (1992) for a discussion of the regional geological setting and to Sketchley (1986) for a review of alteration and mineralization.

■ Surf Inlet Mine — MINFILE 103H 027:

This small north coast mining operation produced gold, copper and silver from two veins of pyrite-bearing quartz within a shear zone in quartz diorite and chlorite schists of the Coast plutonic belt. The two veins have an average width of 3 metres over their strike length of 350 metres but they can be up to 13 metres wide. The veins follow a north-trending shear zone and dip from 40 to 60 degrees to the west; ore shoots rake to the south at about 45 degrees. At surface the veins are about 30 to 50 metres apart but they merge into a single, larger vein at a depth of 170 metres.

The veins contain auriferous pyrite, native silver, chalcopyrite and other copper sulphide minerals in a matrix of quartz, ankerite and brecciated wallrock. The highest ore grades correlated with zones containing abundant sulphide minerals and were generally found in schists rather than the intrusive rocks.

■ Red Mountain — MINFILE 103P 086:

This prospect occurs in a glacial area in the Coast Plutonic Complex that is underlain by intruded sequences of interbedded Jurassic volcanic and sedimentary rocks, possibly as young as Late Jurassic in age. An Early Jurassic grandodiorite stock in which tourmaline, axinite and gold-bearing pyritic zones have been found is located in the northern part of the property. Some younger Jurassic intrusions are possibly also present. In addition, two nearby historically known molybdenum prospects are associated with Tertiary quartz monzonite intrusions.

At the main zone of interest, the Marc zone, two steeply dipping mineralized shear zones have been explored where the zones intersect at surface. The auriferous zones consist of gossanous pyrite-rich, pyrrhotite-bearing sulphides and have been traced over distances of 350 and 500 metres near the grandodiorite contact.

■ Pacific Plate Margin:

A modern analog to the structural setting in which mesothermal fluids are generated may be the active convergent margin of southern Wrangellia where the Juan de Fuca (Pacific) plate is being consumed under North America along the Cascadia subduction zone (Hyndman *et al.*, 1990; Calvert and Clowes, 1991). Two seismic reflector zones under Vancouver Island at 4 to 5 and 7 to 10 second depths on Lithoprobe seismic sections (reflectors 'C' and 'E') are interpreted to be the sources of hot, saline fluids in zones with 1 to 4 per cent porosity (Hyndman, 1988). The fluid sources may be the dehydration of underlying downgoing ocean crust or the deep tongue of accreted sediments. These fluids might

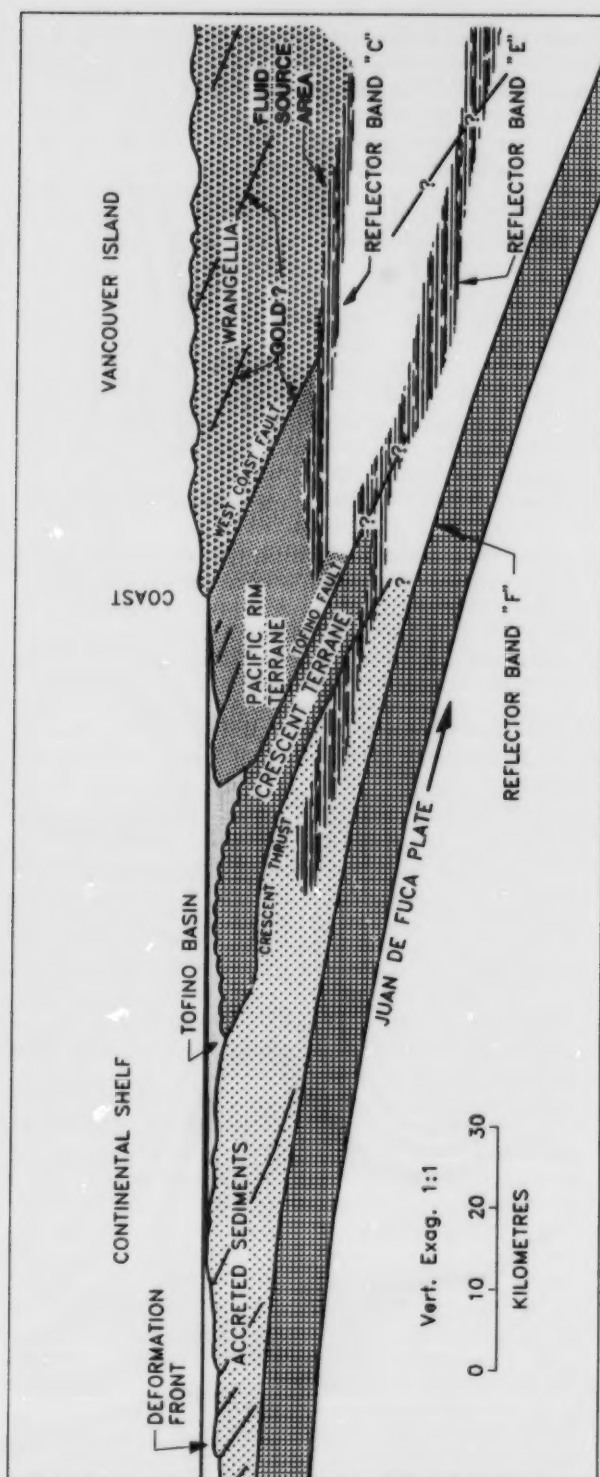


Figure 7-11. Model cross-section for Vancouver Island margin, from Hyndman et al. (1990). Fluid generated in reflector bands "C" and "E" might give rise to mesothermal gold deposits along major fault zones at 10 to 15 kilometre depths along major fault zones.

well be forming mesothermal gold deposits at 10 to 15 kilometre depths along the Tofino and Leech River faults at the boundary of the Pacific Rim terrane and the San Juan, Westcoast or other inboard, major faults on Vancouver Island (Wrangellia), as shown on Figure 7-11.

SUMMARY

A distinct geodynamic setting and hydrothermal regime have been recognized in the genesis of mesothermal deposits, namely the decoupling of the mantle lithosphere in a continent-margin collisional tectonic regime that leads to a sequence of magmatic, hydrothermal and mineralizing events. These include:

- Terrane accretion, commonly with transpression and/or transtension in an oblique subduction regime.
- Structural thickening of the crust with heating and probable anatexis at the base of the thickened crust.
- Metamorphism with dehydration of subducted lithosphere at depth and migration of fluids upward along the major structural conduits; early mineralization?
- Sodic (tonalitic or trondhjemitic), rarely calc-alkaline magmatism.
- Rapid uplift, elevation of isotherms and establishment of steep thermal gradients.
- Structural extension marked by molasse-type sedimentation in narrow fault-bounded, flanking basins.
- Mineralization by large-scale hydrothermal circulation systems; possibly some overprinting and remobilization of older mineralization.
- Late, volumetrically minor alkaline to major calc-alkaline magmatism, the latter ranging from dikes to major, batholithic bodies.

Chris Ash (Ash and Macdonald, 1992) has conducted a study in British Columbia that includes many of the Province's major mesothermal deposits and districts. Their main concerns are lode gold deposits that are associated with oceanic (ophiolitic) ultramafic rocks and display listwanite (carbonatized ultramafic) alteration consisting of quartz-carbonate-fuchsite-talc-sulphide $\pm$ serpentinite. The investigation focuses on the lithotectonic setting of the lode gold deposits and their ophiolitic hostrocks and the timing of gold mineralization during the various tectonic and plutonic events that take place during continent margin accretion.

MESOTHERMAL TO EPITHERMAL TRANSITIONAL DEPOSITS

British Columbian examples of transitional deposits — intrusion-related mineralization in settings with P-T environments that exceed epithermal conditions, are found in the Sulphurets area (see

discussion in the section on Mesothermal deposits), Equity Silver mine, possibly at Big Missouri and Mount Washington deposits and perhaps even at the Eskay Creek deposits. The latter are more likely to represent transitions between volcanogenic massive sulphide deposits and their subaqueous underlying epithermal-style quartz stockwork feeder systems.

■ **Equity Silver mine** — MINFILE 093L 001:

This is a volcanic-hosted silver-copper-gold (antimony-arsenic) ore body associated with Eocene intrusive activity. A quartz monzonite intrusion gave rise to porphyry copper-type, high salinity, hot (>440°C) fluids that evolved with time through intermediate to dilute compositions and temperatures around 200°C during late mineralization (Wojdak and Sinclair, 1984). High temperature aluminous alteration assemblages include andalusite, pyrophyllite, scorzalite (a variety of lazulite), corundum, diaspore and dumortierite; superimposed on this alteration suite is an assemblage with sericite/illite-kaolinite-chorite-carbonate. Tourmaline is present in a clay-altered brecciated zone that extensively overlies and flanks the ore zones. A younger alkalic gabbro stock thermally overprints some of the ore and its alteration zone.

The Equity Silver ore bodies formed in an epizonal plutonic environment from hydrothermal fluids that were, initially at least, too hot and saline to be 'epithermal', *sensu stricto*. They represent mineralization in a *transitional* setting between porphyry copper and epithermal deposits (Cyr *et al.*, 1984).

■ **Eskay Creek** — 21B, 21C, TOK, Pumphouse Creek and 21A zones — MINFILE 104B 008:

The origin and genetic classification of this deposit are controversial. Stratiform base metal massive sulphides suggest a volcanogenic origin. The underlying vuggy quartz-sulphide stockwork, bonanza gold and silver grades and marked vertical and lateral base metal-precious metal-arsenic-mercury zoning patterns suggest epithermal-style mineralization.

Most of the mineralization occurs in the 21B zone which forms a stratabound sheet within a thin sequence of carbonaceous mudstone that lies between footwall felsic volcanoclastic rocks and hanging wall pillowed andesitic flows and breccias. The host rocks are Early to Middle Jurassic in age and considered to be correlative with the Hazelton Group. The deposit consists of stratiform lenses of semi-massive to massive sulphides containing pyrite, tetrahedrite, boulangerite, bournonite and galena with electrum. The footwall zone consists of high-grade, bonanza-type quartz veins.

The southern portion of the deposit termed the 21A zone also consists of stratabound gold-bearing semi-massive sulphides in the 40-metre-thick black argillite unit. Footwall rocks are intensely altered by quartz and sericite/illite with disseminated and stockwork sulphides and some gold. Mineralization

below the massive sulphide zone exhibits vertical zoning containing, from surface to depth (Ettlinger and Roth, 1991): Cinnabar (only in upper portion of zone), stibnite+realgar+orpiment (within and immediately below semi-massive sulphide zone), stibnite, pyrite + sphalerite + galena, galena + tetrahedrite + pyrite, pyrite. A general description of the geological setting of the Eskay Creek deposit is provided by Britton *et al.* (1989).

EPITHERMAL DEPOSITS

DEPOSIT TYPES AND MINERALOGY

Knowledge of epithermal deposits has expanded remarkably during the past decade because they have been the focus of much, if not most, recent exploration attention. This is due mainly to their importance as a source of precious metals. Also it is now recognized that epithermal deposits may have present-day analogs in active and extinct geothermal fields. A wealth of new information provides deposit descriptions, process-related studies and reviews. Key references are discussions by: Buchanan, 1981; Berger and Eimon, 1983; Berger and Bethke, 1985; Hayba *et al.*, 1985; Heald *et al.*, 1987; Berger and Henley, 1989; Sillitoe, 1989, 1991a and in press; Hedenquist *et al.*, 1990; White and Hedenquist, 1990; Henley, 1991 and many others.

Epithermal deposits were once thought to be exclusively Tertiary in age and associated mainly with silicic volcanism in structural depressions (calderas and grabens). Now exploration and research interests are focused on other magmatic environments including stratovolcanos, Cordilleran volcanic belts and ocean islands that range in age from Quaternary in the Circum-Pacific region to Mesozoic in the Canadian Cordillera to Paleozoic in Australia (White and Hedenquist, 1990). Although some of the largest mines are in Tertiary rocks, recent spectacular exploration successes have taken place in Quaternary volcanic island systems (Lihir Island, Papua-New Guinea and Hishikari, Japan) as well as in accreted continent-margin settings (McLaughlin, California). These three recently discovered deposits (Henley, 1991, and company reports) collectively contain in excess of 800 tonnes gold (Ladolam deposit, Lihir Island 573 tonnes reserves with additional large geological resources; Hishikari 140 tonnes; McLaughlin 100 tonnes gold).

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The most fundamental model for epithermal mineralization is any in which a high-level hydrothermal fluid ascends towards surface, undergoes cooling and chemical changes and resulting mineralization takes place in a near-surface (less than two kilometre depth) to hot spring environment. A particularly useful starting point for discussions is provided by the geometrically pleasing model of Buchanan (1981), shown on Figure 7-12, and his accompanying compilation of the diagnostic characteristics of over 60 epithermal deposits.

Buchanan's model describes zones of mineralization that form along a dominant subvertical fracture system from a depth of about 500 metres to the surface; close to surface it splits into a series of subsidiary structures. The centre of ore deposition, placed by Buchanan at a depth of about 350 metres, has a discrete top and bottom. Above the ore, quartz veining persists but diminishes progressively in abundance upwards, as do precious and base metal amounts. Similarly, quartz becomes progressively

finer grained and is chalcedonic or opaline in the upper parts of the zone. If the hydrothermal fluids discharge at surface as hot springs, mushroom-shaped caps or ponded deposits of siliceous sinter are deposited. Alternatively, in structures with less dynamic flow, surface expressions of deeper mineralization may be nothing more than thin calcite veins, clay-altered zones or small quartz veinlets. Buchanan describes two types of ore terminations at the base of the ore zone. In one type, quantities of ore diminish downward and quartz veins that continue to depth are barren or contain only minor sulphides. In the second more common type, precious metals and sulphide minerals occur in subeconomic amounts. In both cases, calcite and adularia contents decrease with depth.

Buchanan concluded that ore deposition and attendant wallrock alteration result from 'boiling' (some type of phase separation) and oxidation of the ascending hydrothermal fluids. Repeated self-sealing by mineral deposition is followed by episodic refracturing and brecciation along the ore structure. Pressure drops cause phase separation (commonly carbon dioxide effervescence) that causes mineral precipitation. This produces multiple stages of ore deposition, and the distinctive, layered, crustified and symmetrically-banded ore textures. The depth at which phase separation, or so-called 'boiling', takes place is controlled mainly by the temperature and concentration of solutes; hydrostatic fluid pressures are prevalent in this largely open-fracture system but pressures may rise when veins become plugged and sealed.

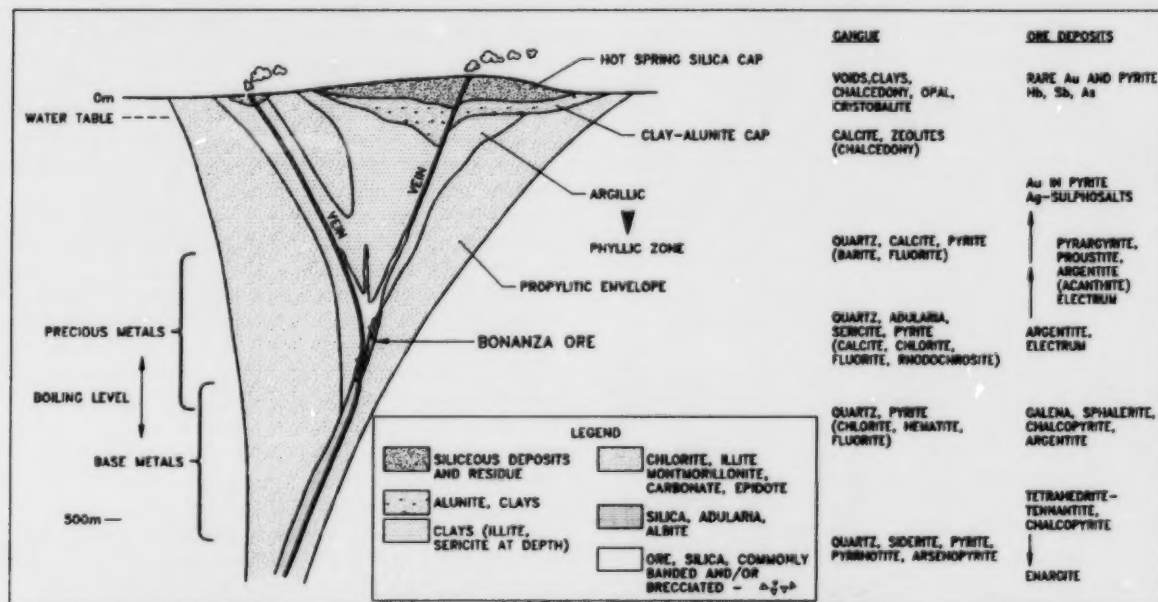


Figure 7-12. Idealized section of an epithermal deposit, after Buchanan (1981). Real systems are usually more complex because this single stage model is overprinted by several stages of mineralization related to migration of fluid boiling or degassing levels.

Buchanan's major contribution remains that he provides an empirical description of ore and alteration mineral zoning and describes the spatial relationship between mineralization and the paleosurface. Undoubtedly most natural mineralizing systems will be more complex than Buchanan suggests. Nevertheless, the model is useful. Once the position of the paleosurface has been recognized from geological data or has been postulated for a mineralized area, this model can be used to estimate depth of mineralization.

Subsequent to Buchanan's and other early 1980s discussions, the deposits were assembled into two main types, as shown in Table 7-6. The two styles of volcanic-hosted epithermal deposit now recognized are: **adularia-sericite** (or low-sulphidation) and

alunite-kaolinite (or high-sulphidation, acid sulphate) types (Hayba *et al.*, 1985; Heald *et al.*, 1987). The possible genetic relationship between these deposits and other gold-bearing deposit types such as the Carlin deposits, porphyry copper-molybdenum and other deposits are discussed by Bonham (1989), Berger and Henley (1989), Sillitoe and Bonham (1990), among others. Sillitoe (1989, 1991a, 1991b) offers some particularly enlightened discussion about the inter-relationships of the many types of hydrothermal deposits in volcano-plutonic arcs. The geological setting of the two deposit types determines what mineralogical type they are. Their origin and style, largely influenced by the presence or absence of subvolcanic intrusions and magmatic fluids, is discussed below in the section dealing with

TABLE 7-6

Characteristics of the Adularia-sericite and Alunite-kaolinite (or high-sulphidation, acid-sulphate) type Epithermal Deposits*

	ADULARIA-SERICITE	ALUNITE-KAOLINITE
Other names	low-sulphur, low-sulphidation, adularia-sericite (illite) type, bonanza type, geothermal type	high-sulphidation, high-sulphur, enargite gold, advanced argillic, alunite-kaolinite $\pm$ pyrophyllite-type Nansatu-type, quartz-alunite, volcanic-hosted Cu-As-Sb
Structural setting	structurally complex volcanic environments, calderas, grabens, stratovolcanoes	intrusive centres, caldera margins, collapse structures, breccia pipes, flow dome complexes, diatremes
Age of ore and host	ages of host and ore distinct (>1 Ma)	similar ages of host and ore (<0.5 Ma)
Mineralogy	electrum, native Au and Ag, argentite, sulphosalts, tetrahedrite/tennantite, sphalerite, galena, chalcopryrite, pyrite, selenides, tellurides	pyrite, enargite, native gold, electrum, covellite, chalcopryrite, chalcocite, bornite, no selenides, tennantite/tetrahedrite
Ore commodities	Au, Ag, Au $\pm$ Ag, Ag $\pm$ Au, minor Pb, Zn, Cu	Au, Cu, Ag
Alteration	closely related to veins. Open space filling; banded to crystalline quartz with abundant chalcedony. Adularia, sericite/illite, calcite, propylitic; locally alunite, some kaolinite and mixed layer clays; barite, fluorite, Mn minerals and chlorite common	areally extensive, massive replacement to vuggy quartz. advanced argillic to argillic, pyrophyllite $\pm$ sericite. Abundant hypogene kaolinite , extensive hypogene crystalline alunite , barite, calcite absent, chlorite rare; locally native sulphur
Temperature	100–300°C	100–350°C, high temperatures early, low temperatures later
Salinity	0 to 13 wt% NaCl equivalent, commonly < 3 wt%	1 to 24 wt% NaCl equivalent, early high salinity, later dilute
Source of fluids	dominantly meteoric	meteoric with significant magmatic component
Sulphide sulphur source	deep-seated, multiple sources leached from depth, reduced	deep-seated magmatic, oxidized

* "Alunite-kaolinite" is the preferred name by Berger and Henley (1989) and Henley (1991) for acid-sulphate or high-sulphidation-type deposits. After Hayba *et al.* (1985), Heald *et al.* (1987), White and Hedenquist (1990), Henley (1991), and Sillitoe (in press).

hydrothermal fluid hydrodynamics in volcanic environments. The distinguishing characteristics of the two types of deposits are listed in Table 7-6.

The two types of deposits co-habit many epithermal districts, for example in the southwestern Pacific island arcs and Andes, but they are not intergradational and transitions between the deposit types are not evident. Generally acid-sulphate deposits are subordinate in number to the adularia-sericite type. They can, however, be very large and are, therefore, highly valued exploration targets, for example, El Indio, Chile and Lepanto, Philippines. Significantly, the Canadian Cordillera lacks well described acid-sulphate type ore deposits, although a number of occurrences of acid-sulphate alteration are known (Panteleyev, 1992) and have received some exploration interest. Advanced argillic, high-temperature aluminous alteration, but lacking significant sulphate minerals, has been described at the Equity Silver mine (Cyr *et al.*, 1984; Wojdak and Sinclair, 1984). A number of zones with acid sulphate alteration assemblages are recognized to be small, near-surface acid reflux zones in the upper, oxidized acid-leached parts of adularia-sericite deposits in the Toodoggone area (Diakow *et al.*, 1991).

In addition to the two main mineralogical deposit types — adularia-sericite and alunite-kaolinite, some model subtypes have been proposed, mainly to satisfy variations from the norm in specific deposits. Two subdivisions that are useful are the *alkalic* and *hotspring* models proposed by Bonham and Giles (1983) and Bonham (1984, 1989). Mineral deposits in alkalic environments have been discussed by Mutschler *et al.* (1986) and Mutschler and Mooney, (in press). The alkalic subtype, which commonly contains abundant telluride mineralization and locally prominent fluorine and/or vanadium-rich alteration, can be regarded to be a variant of the adularia-sericite type. The hotspring precious metal deposits, with or without mercury-antimony (arsenic) mineralization such as at McLaughlin, California (Lehrman, 1986) or chalcedonic sulphur-bearing fumarolic deposits in the Chilean Andes (Sillitoe, 1991b), may simply represent surface manifestations of deeper epithermal deposits. An additional subtype proposed by Sillitoe (in press) may be low-sulphidation systems with relatively abundant sulphides and sericite-dominant alteration.

GEOLOGICAL SETTING AND HYDROTHERMAL FLUID HYDRODYNAMICS IN EPITHERMAL ENVIRONMENTS

The two mineralogically distinct deposit types result from mineral deposition in fundamentally different geological settings with contrasting fluid sources, circulation paths, cooling histories and depositional sites. The low-sulphidation, adularia-sericite type is formed from predominantly meteoric water convection cells in fossil-geothermal and

hotspring settings within structurally extended zones, commonly in areas with predominantly sub-aerial silicic volcanism. Typical environments are the continental volcanic, caldera-related deposits of the southwestern U.S.A., such as Creede, Colorado; also back arc extension-related volcanic zones such as the Taupo volcanic zone in the North Island of New Zealand (Henley *et al.*, 1986) or strike-slip-related, transtensional continent-margin settings such as McLaughlin, California (Lehrman, 1986). The highly-sulphidized, acid-sulphate deposits are derived from upwelling, magmatically-supplied and driven, intrusion-related fluid systems in stratovolcanoes, domes and dome-flow complexes within magmatic arcs.

Typical deposits are found in the young volcanic island arcs and continent-margin arcs throughout the circum-Pacific rim, notably the western Pacific and South American Andean regions (Sillitoe, 1989; Hedenquist *et al.*, 1990; Sillitoe and Camus, 1991). In addition, young subduction-related intra-continental arcs such those in the southeastern European-Anatolian-Caucasian and western Himalayan alpine belts contain subvolcanic porphyry copper-gold deposits and, therefore, probably epithermal deposits as well (Sawkins, 1990; Sillitoe, in press). The two main hydrothermal settings were described by Henley and Ellis (1983) in a paper comparing ancient and modern geothermal systems. Their model, influenced by earlier works by Ransome (1909), White (1955, 1981) and Elder (1981), is the acknowledged or implicit basis for virtually all subsequent representations of volcanic-hydrothermal flow regimes. The Henley-Ellis hydrodynamic flow model, embellished to consider sulphur-source isotopic systematics by Rye *et al.* (1989), is shown on Figure 7-13 to illustrate the diverse origins of alunite and acid-sulphate alteration. The following discussion paraphrases Rye *et al.* and Berger and Henley (1989) and accompanies Figures 7-13 and 7-14; other volcanic-related sites and structures are also important, as discussed below:

■ **Figure 7-13 A:** Stratovolcanos around the Pacific Rim or volcanic dome and dome-flow complexes in continental volcanic settings display volcano-related hydrothermal systems with possible **magmatic-hydrothermal, magmatic steam and steam-heated acid-sulphate environments.** Magmatic-hydrothermal and steam-heated environments can be present both contemporaneously or sequentially. The deeper magmatic-hydrothermal environment results from disproportionation of magmatic SO_2 , whereas the overlying steam-heated environment is a product of oxidation of H_2S at the water table. Overlying steam-heated waters mix with the deeper magmatic fluids along the top of the zone of condensation. Overprinting of early magmatic-hydrothermal assemblages by convecting steam-heated waters

or down-flowing acid condensates during the waning stages of hydrothermal activity is common.

Plutons at depth may develop porphyry-type copper, copper-gold, copper-molybdenum or molybdenum mineralization. Initially the ascend-

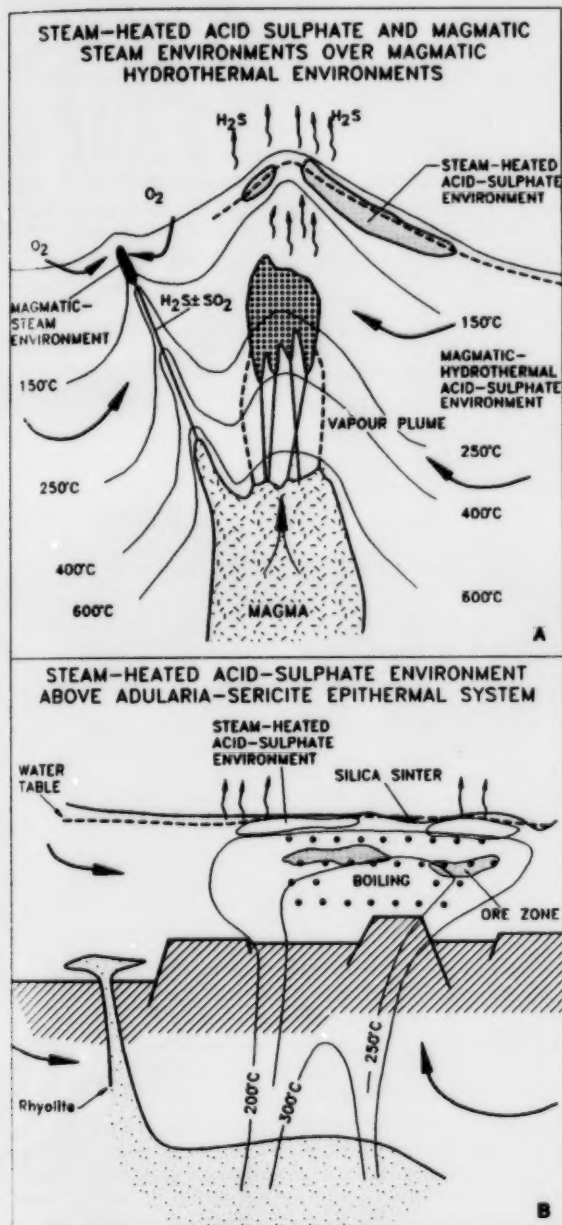


Figure 7-13. Volcanic setting of acid-sulphate, alunite-kaolinite (A) and adularia-sericite (B) mineralizing hydrothermal systems. The geological setting is from Henley and Ellis (1983); this figure and fluid descriptions are after Rye et al. (1989) based on stable isotope systematics.

ing hydrothermal plume causes extensive leaching with attendant alteration and increase in permeability of hostrocks within the fluid conduits. Zones of advanced argillic alteration may form due to condensation of acidic magmatic gases in the upper portions of the active volcano. Acid lakes can form in summit craters or steaming ground and acid mud ponds may be present in active acid-leached zones. At some later time, ground water convection systems envelope the highly permeable brecciated and leached altered rocks. The age relationships in high-sulphidation deposits are variable with evidence in some for contemporaneous gold deposition and advanced argillic alteration. The interaction of magmatic discharges with meteoric water might be necessary to condense metals in high-level volcanic environments and create a situation conducive to mineralization (Hedenquist and Aoki, 1991).

- Figure 7-13 B: Geothermal systems form adularia-sericite deposits at depth from mainly meteoric-source, near-neutral to mildly alkaline, dilute chloride waters. The buoyant fluids ascend, displace the overlying fresh ground waters and mix along the side and top of the hydrothermal plume. Boiling may occur near surface with fractionation of volatiles, mainly H_2O and CO_2 , into the vapour phase. The rising vapours (steam) heat the overlying groundwaters, condense and slightly acidify them by hydrolysis reactions of H_2S and CO_2 (Bethke, 1988). The attendant alteration is argillic-type with sericite or mixed-layer clays. If the volatiles rise above the water table, sulphuric acid is produced by oxidation of H_2S and intense acid-sulphate alteration takes place. During the waning stages of hydrothermal flow and curtailed meteoric recharge, the near-surface acid-sulphate condensates may descend and overprint the deeper alteration assemblages to form an acid-leached zone. A similar-appearing acid-sulphate kaolinite-rich supergene assemblage can also form in sulphide-bearing rocks by weathering processes. Distinctions between hypogene and supergene argillic and acid-sulphate, advanced argillic alteration can be made by careful study of alteration mineralogy, chiefly the nature of the alunites (Thompson and Petersen, 1991; Sillitoe, in press).

Acid-leached zones may be underlain by thin stratabound zones of massive, dense silicification called 'silica caps'. These generally form in permeable strata such as pyroclastic rocks or hydrothermal breccias as thin layers, rarely more than one metre in thickness. The silicified zones are believed to be formed immediately below the paleo-water table (Sillitoe, in press). They are generally sub-economic and contain only pyrite mineralization. Gold is rare in the silica caps and, where present, is patchy in its distribution and present in only minor amounts. Native sulphur and cinnabar can be deposited above the water table by fumarolic activity. Hydrothermal fluids that issue onto the ground surface and

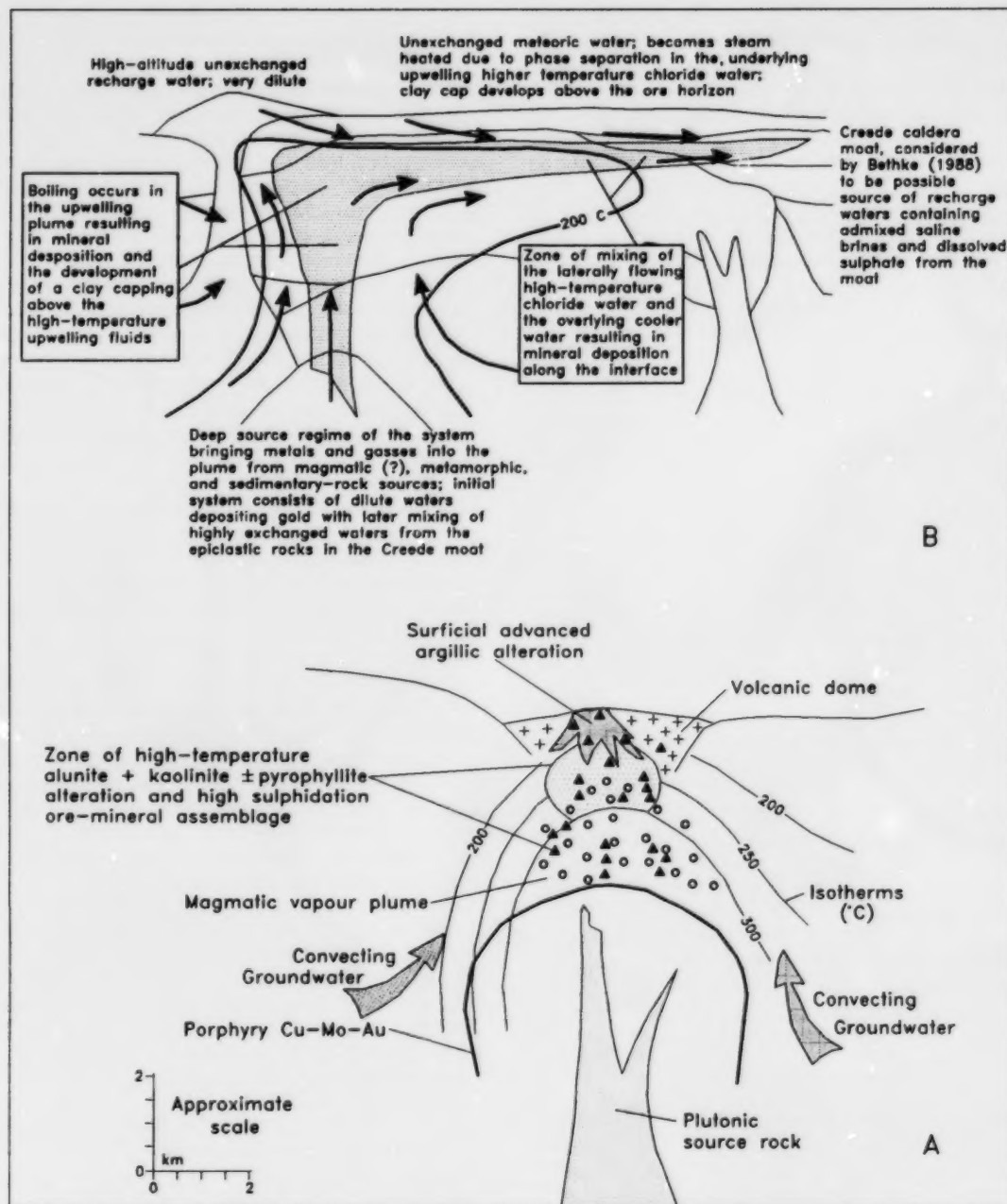


Figure 7-14. **A** — Acid-sulphate (alunite-kaolinite $\pm$ pyrophyllite) hydrothermal system in the upper portion of an active volcano, above a porphyry Cu $\pm$ Au, Mo system at depth. Mineralization takes place when older acid-sulphate altered rocks react with normal adularia-sericite-type fluid. Variations in deposits are due to different amounts of interaction and mixing of downward-flowing steam heated waters with upwelling entrained meteoric or sea water, after Berger and Henley (1989); also see Stoffregen (1987). **B** — Fluid dynamics in upflow (vertical) and outflow (lateral left to right), Creede, Colorado, adularia-sericite-type system, after Bethke (1988) from Berger and Henley (1989).

ponded or flow into pools, form hot spring sinters or terraces from silica precipitates.

The recognition of **fluid upflow** compared to **out-flow** patterns in the two volcanic hydrothermal environments discussed above is critical to effective exploration. The upflowing parts of hydrothermal systems tend to be magmatically driven fluids in steep structures. These are the hottest parts of the systems in which vapour separation occurs and mineral deposition takes place. The zones are marked by advanced argillic alteration and vuggy (slaggy) silica-rich rocks produced by strong acid leaching. Advanced argillic alteration in the uppermost portions of the hydrothermal systems results from strong acid leaching and acid-sulphate alteration only if oxidation of H_2S takes place above the water table and condensate drain-back occurs. Where dilution of condensates by groundwater takes place,

hydrothermal fluids can be moderate to weakly acidic. Similarly, fluids passing outward from hydrothermal conduits into flanking or peripheral zones can be neutralized by wallrock interactions. These alteration assemblages contain sericite/illite, kaolinite, mixed-layer clays and grade into flanking zones with propylitic alteration. Note that phase separation occurs in fluid conduits in most geothermal systems and some interaction of upflowing or out-flowing steam-heated waters with overlying groundwater is probable.

The lateral outflow portions of deposits are gravity driven and, therefore, dependent on topographic gradient. Adularia-sericite deposits and their superjacent argillic/advanced argillic alteration zones, generally form in extensional structural settings and tend to be spatially constrained to their hydrothermal conduits. Alunite-kaolinite systems, on the other

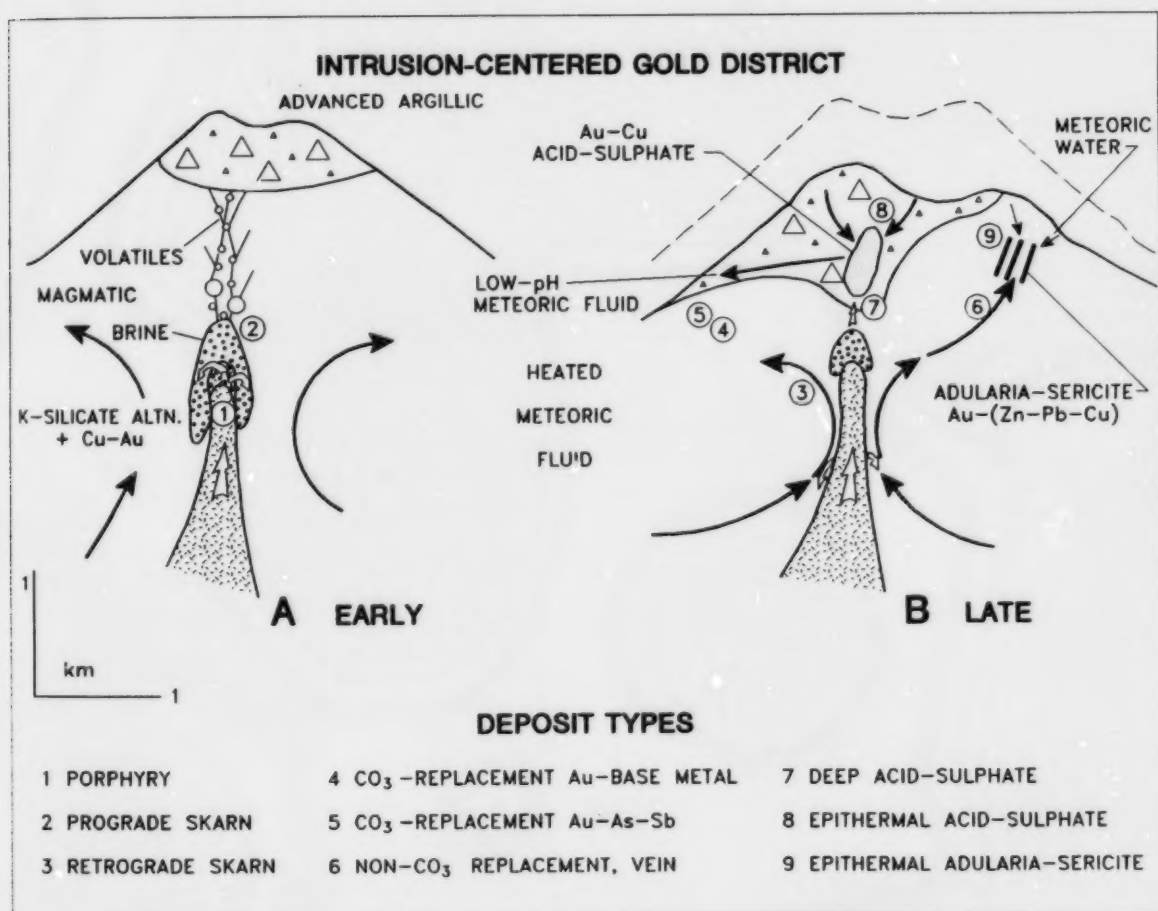


Figure 7-15. Model for an intrusive-centred gold district, after Sillitoe (1989, 1991a). Stippling shows area of magmatic, low salinity two-phase vapour plume with surrounding groundwater system, after Henley and McNabb, 1978. Note that the lapsed time from early to late hydrothermal activity (A to B) is adequate for volcanic collapse and much erosion to take place, especially in island arc environments and late-stage near-surface mineralization may overlap early-stage deep mineralization within a single mineralizing system. The distinctions between hypogene and supogene processes may be indistinct.

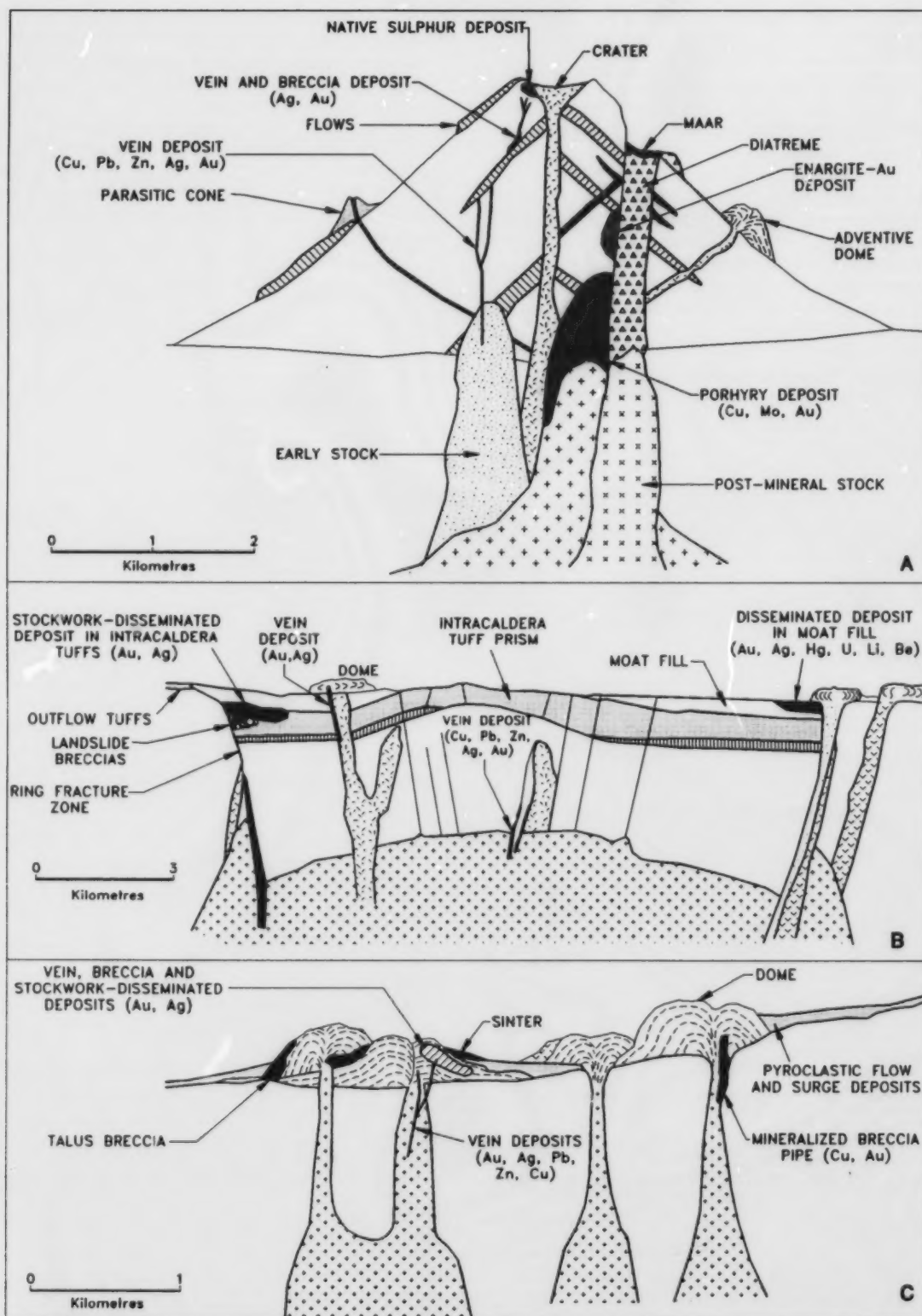


Figure 7-16. Volcanic landforms, showing models of idealized sites for mineralization, after Sillitoe and Bonham (1984). (A) stratovolcano, (B) caldera (resurgent) and (C) flow-dome complex.

hand, are commonly underlain by plutons and therefore have long-lived, high heat flow. They can have a large hydrostatic head in stratovolcano terrains, leading to much mixing with local waters. The mixed outflowing solutions emerge at surface as hot springs or follow permeable lithologies down slope. The resulting alteration forms large, laterally extensive but thin argillic zones that generally lack ore-grade mineralization. The separation of mineralized upflow structures and their barren outflow zones can be in the order of 2 to 4 kilometres, and rarely up to 20 kilometres. Geological evidence for the proximity of dynamic, upflowing portions of mineralized systems can be hydrothermal, phreatic eruption or phreatomagmatic breccia zones. Phreatic explosions, alternately known as hydrothermal eruptions, are those in which groundwater converts to steam; phreatomagmatic eruptions take place where magma comes into contact with groundwater. Convecting hydrothermal systems that have small heat budgets or slow water recharge rates tend to have little surface expression of deeper hydrothermal activity.

The life span of individual geothermal fluid circulation cells can be relatively short — 10^4 to 10^5 years at typical discharge rates of 400 kilograms per second (Henley and Hoffman, 1987). Fluid flow in any given site within a geothermal field can be ephemeral and transient. If enough heat is provided, say above cooling plutons or subvolcanic intrusions, a series of fracture and breccia-controlled conduits can be superimposed in an area giving rise to sequential ore deposition. Figure 7-14 shows two examples of the contrasting hydrothermal fluid-flow regimes. The Creede, Colorado, model shows upflow, lateral flow and mixing with steam-heated and meteoric waters in the zone of mineralization, and outflow into the caldera moat. The second part of the figure shows a magmatically derived, upflowing, vapour-rich fluid with acid-sulphate-type mineralization in a volcanic dome complex. Note the small amount of upflow and high-temperature acid-sulphate alteration (alunite-kaolinite-pyrophyllite) shown in this setting compared to the laterally extensive acid-leached argillic alteration blanket on the slopes of the stratovolcano depicted in Figure 7-13.

The rapid volcanic construction, uplift and erosion of stratovolcanoes with probably multiple intrusive-volcanic sequences leads to protracted lives of hydrothermal systems and can result in the superimposition of multiple-stage mineralization. As shown on Figure 7-15, after Sillitoe (1989, 1991a), early acid, vapour-rich pluton-related alteration and mineralization may have later, cooler mineralization superimposed upon it. In some cases this leads to blurring in distinctions between hypogene and supergene alteration (and alunites). A fine discussion of episodic sulphide deposition, indicating fluctuating chemical conditions is provided for Summitville, Colorado, by Stoffregen (1987). Terminating late stages of this type of mineralization can take place in relatively cool conditions. For example at

Goldfield, Nevada, the final collapsing convective system deposited marcasite as mammillary crusts on earlier sulphides in the rhyodacite hostrock (Berger and Henley, 1989).

VOLCANIC ENVIRONMENTS AND DEPTH-ZONING RELATIONSHIPS OF EPITHERMAL AND RELATED DEPOSITS

Deposit descriptions and genetic interpretations of southwest U.S.A. Tertiary deposits mainly by researchers of the United States Geological Survey has led to extensive comparisons of those districts with Canadian deposits and northern Cordilleran geological environments. Unfortunately, too much emphasis has been placed in Canada on the caldera or resurgent caldera setting and genetic relationships of the deposits. There has been a widely held notion that calderas are a requisite for the development of epithermal deposits. This is not the case. In fact, calderas, as described in a classic paper by Smith and Bailey (1968), are simply one type of specialized volcano and do not inherently contain any mineralization. In Nevada, for example, only two out of 31 recognized calderas are known to contain ore (McKee, 1979), and in the western U.S.A., only 14 out of 125 calderas have any known associated ore (Rytuba, 1981). If mineralization occurs in calderas or resurgent calderas it is because they produce large fracture systems, but any major fracture system that channels hydrothermal fluids can localize mineralization.

Other structural controls that provide fluid conduits (Sillitoe, in press) are: ring and radial fractures related to calderas that intersect regional faults; steep normal or strike-slip faults, notably at bends and dilational jogs; districts where there has been repetitive dilations in fault zones during protracted tectonic activity (referred to at McLaughlin, California as 'seismic structures'); listric faults; sets of conjugate fracture systems; and breccia pipes or ring fracture diatremes.

Radiometric data from epithermal deposits in Tertiary volcanic areas of the southwestern U.S.A. generally show that, at least in the case of adularia-sericite systems, the ores are considerably younger than the caldera-forming volcanism. Thus it seems that hydrothermal activity is not related to caldera volcanism but is related to younger, subvolcanic magmatic activity in structurally disturbed rocks at caldera margins and in the surrounding rocks. On the other hand, the smaller collapse craters in stratovolcano summit areas, many containing acid lakes, are coeval with underlying hydrothermal systems of the acid-sulphate type.

Association of some epithermal ores with felsic volcanic rocks is evident (rhyolite and dacite flows, domes, ash-flow sheets and tuffs). But the relationship between mineralization and these rocks has also been over emphasized. Epithermal ores occur in all rock types, particularly those that sustain large,

open-fracture systems over extended periods of time during hydrothermal activity. In Nevada, McKee (1979) noted that in 98 mining districts with economically significant ore production, only five districts were in siliceous tuffs; the majority of mineral deposits were in *andesitic* hypabyssal and extrusive volcanic rocks. Andesitic rocks appear to preferentially develop and retain fault and fracture-related dilatant structures and openings during mineralization. In addition, and probably of secondary importance, andesitic pyroclastic rocks or flow breccias maintain high primary permeability during hydrothermal activity. Acidic rocks with extensive welded units can have limited primary permeability and during hydrothermal activity fractures in these rocks tend to 'plug up' with hydrothermal clay minerals.

The diversity of volcanic environments in which high-level magmatic systems and related hydrothermal activity takes place is discussed by Sillitoe and Bonham (1984). They recognize four main environments of mineralization, each with its own distinctive volcanic landform: stratovolcano, flow-dome complex, caldera and maar. The three main features of importance in the Cordillera are shown on Figure 7-16. The importance of flow-domes as sites of mineralization is illustrated by Cunningham *et al.* (1991). Maar structures — large, circular depressions marking sites of repeated, phreatomagmatic eruption, are seen as diatremes with surrounding tuff rings; a number are intruded by domes. They can be highly mineralized, for example, Cripple Creek, Colorado, but are not illustrated here. A rare example recognized in British Columbia, the Wolf prospect, has recently been described by Andrew (1988).

MAJOR BRITISH COLUMBIA EPITHERMAL DEPOSITS

Currently the most economically important and best-described epithermal deposits in British Columbia include the Early Jurassic precious metal deposits in the Stewart and Toodoggone River areas and the Tertiary Blackdome and Cinola deposits, as summarized below. Other epithermal deposits listed in Table 7-3 are briefly described.

■ Premier Gold Mine — MINFILE 104B 054:

The largest epithermal silver-gold deposit in the province, site of the former Silbak Premier mine and a number of nearby, similar deposits such as the Big Missouri mine, resemble sericite-rich varieties of adularia-sericite-type deposits. Hostrocks are Late Triassic to Early Jurassic andesitic to dacitic volcanic rocks of the Unuk River Formation and are correlative with the Hazelton Group. The volcanic rocks are intruded by Early Jurassic porphyry dikes that are considered to be subvolcanic members of the Texas Creek plutonic suite. A potassium-feldspar porphyry, the 'Premier Porphyry' is spatially associated with the ore. Mineralization with quartz-carbonate-sulphide cemented breccia veins took

place repeatedly in conjugate fault sets and breccias formed in the volcanic rocks at the locus of a number of the porphyritic intrusions.

There are a number of styles of mineralization ranging from quartz vein, quartz-sulphide stockwork and siliceous breccia to layered, thinly banded to massive sulphide-rich ores. Sulphide content varies from generally less than 5 per cent locally to as much as 75 per cent. Ore minerals include native gold and silver, electrum, payrargyrite, polybasite, and argentite with pyrite, sphalerite, galena and minor tetrahedrite, chalcopyrite, arsenopyrite and locally pyrrhotite. Gangue minerals in veins are quartz, carbonate, chlorite, sericite and potassium-feldspar. The gold content in the deposits shows considerable lateral variability and vertical zoning is evident due to a decrease in the silver content with depth. Hydrothermal alteration of ore wallrock consists of silicification with sericite and lesser potassium-feldspar; peripheral alteration is propylitic with alteration assemblages of carbonate, chlorite, sericite and pyrite. Locally an phyllitic foliation is evident in the propylitic rocks.

Mineralization occurs along two main trends within an overall north to northeasterly direction: 1) a northwest-dipping 'Main or Northeast zone' with 60 degree dip at surface but flattening to 30 degrees in the lower mine workings; and 2) vertical to steeply-dipping 'Northwest or West zone' structures. The en echelon ore lenses have an overall deposit strike length of about 1800 metres with a downdip extent of at least 500 metres and an average width of about 10 metres. Most production came from the region within 500 metres of the intersection of the two main ore trends.

These base-metal bearing silver-gold vein deposits are interpreted to be deposited from hydrous fluids at a minimum depth of 500 metres, with temperatures of 250 to 260°C and salinities less than 4.5 equivalent weight per cent NaCl (McDonald, 1990).

■ Cinola (Babe) — MINFILE 103F 034:

A large, low-grade, hot-spring-type gold occurrence is related to the emplacement and hydrothermal brecciation of rhyolite in a Miocene active fault zone. Initial high permeability in the fault zone and adjoining clastic rocks allowed much lateral flow and silicification near the surface. This was followed by several pulses of brecciation of the earlier silicified rocks leading to extensive quartz vein and stockwork development, possibly related to depressurization of hydrothermal fluids during movements along the fault. Argillic alteration is extensively formed peripheral to the silicified zones by mixing between groundwater and steam-heated, near-surface thermal waters. Some acid leaching overprinting is evident. Hydrothermal activity was coincident with sedimentation (and movements along the fault) as quartz vein and hydrothermally altered fragments are present in mud-flow units (Christie, 1989).

The following description is taken from Tolbert and Froc (1988): The deposit represents the mid to upper levels of a hot-spring-type precious metal system. Hostrocks comprise two sedimentary formations — dark grey calcareous mudstones and argillites of the Late Cretaceous Haida Formation and coarse to fine-grained clastic sediments of the Miocene-Pliocene Skonun Formation. These formations are separated by a right-lateral fault with normal, east side down movement. The sedimentary rocks are intruded along the fault by at least two separate rhyolite intrusions of apparent Middle Miocene age. The initiation of hydrothermal and hot-spring activity is related to the emplacement of the rhyolites.

A hydrothermal breccia with coincident and overlapping stockwork silica veining is formed for a distance of at least 800 metres along the intruded portion of the fault. This mineralization is cut by some larger, banded to vuggy quartz veins that have

formed in extensional structures that are oblique to the main fault zone. The Skonun sediments surrounding the hydrothermal breccia are also extensively silicified, both by quartz veinlets and by pervasive silicification. Argillically altered rocks with kaolinite/illite and minor sericite and alunite flank the brecciated and silicified area. The mineralized zone occupies a mushroom-shaped zone when viewed normal to the intruded fault. The orebody is essentially wedge-shaped, approximately 200 metres wide at surface and 50 metres wide at a depth of 200 metres.

Precious metals are localized in the silicified hydrothermal breccia zone in which stockwork veining and oblique, extensional quartz veins are most abundant. Minor amounts of gold are found in quartz veinlets in the peripheral argillic alteration zone. Small amounts of pyrite and marcasite are present throughout the deposit but their amounts cannot be correlated directly with highest gold values. Arsenic,

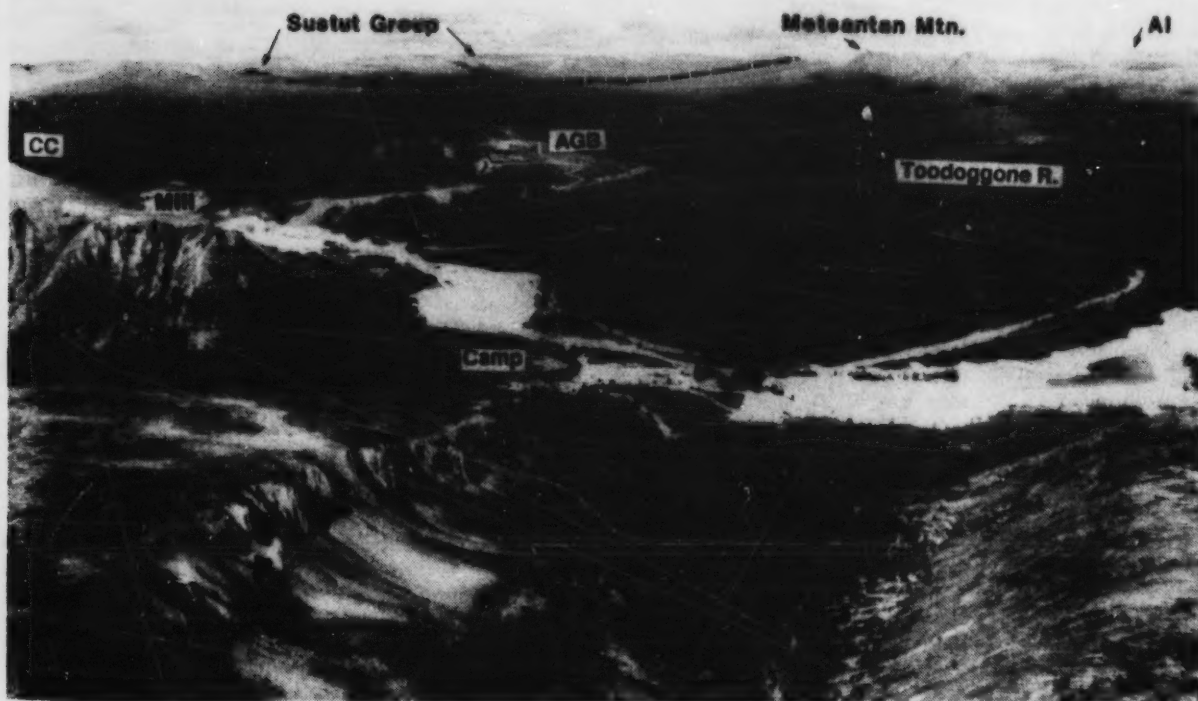


Plate 7-2. Lawyers gold-silver deposit, Toodoggone River area, looking northwesterly. Cheri Gold Mines camp, mill site and the Amethyst Gold Breccia (AGB) and Cliff Creek Zones (CC) are shown in the centre of the photograph. The prominent knoll on which the deposit is located is marked by resistant, silicified hydrothermally altered rocks. Flat-lying Jurassic ash flows of the Toodoggone volcanics are in the foreground. Silica-clay-alunite cappings on Alberts Hump, similar to the advanced argillic alteration with gold-barite veins at the nearby AI deposit, occur north of the Toodoggone River and 5 kilometres beyond Metsantan Mountain. Gently inclined terrigenous sedimentary beds of the Late Cretaceous Sustut Group overlap the Toodoggone rocks to the west and northwest.

antimony and mercury concentrations are evident in generally the upper and marginal parts of the mineralized zone.

■ **Toodoggone Camp** — Lawyers, Baker, Shasta and Al deposits — MINFILE 094E 066, 26, 50, 91:

Epithermal gold-silver deposits in the Toodoggone river area are hosted by Early Jurassic alkali-enriched volcanic rocks that erupted during two major volcanic cycles spanning about 7 million years. Volcanism and related plutonic activity is associated with the structural development of an elongate, volcano-tectonic depression in which a central extensional fracture zone confines the main deposits. Younger sedimentary rocks overlay and protected the deposits from erosion (see Plate 7-2).

Gold and silver mineralization occurs mainly in quartz veins with associated adularia, sericite and calcite. Locally vuggy gold-barite veins are found in extensive zones of intense clay-altered rocks with advanced argillic mineral assemblages. The veins have formed from low-temperature, dilute fluids with compositions typical of epithermal deposits. Marked ^{18}O enrichment suggests that there was considerable magmatic input into the hydrothermal systems.

Radiometric dating of alunite suggests that an early acid-sulphate mineralizing episode occurred around 190 Ma or earlier. This coincides with a volcanic hiatus during uplift and cooling of several plutons. Dates on adularia and sericite from the main gold-silver-bearing quartz veins indicate that this mineralization took place up to three million years later during the latest stages of volcanism and fault block subsidence. A depth zoning model for mineralization (see Figure 7-18) shows gold-barite veins in high-level argillic and advanced argillic alteration zones that formed in acid-leached zones on the flanks of stratovolcanoes. Elsewhere small acid-leached argillic zones with alunite represent the uppermost parts of adularia-sericite hydrothermal systems formed in grabens or half-grabens within the central Toodoggone depression. Refer to Diakow *et al.* (1991) for a more complete discussion.

■ **Blackdome Mine** — MINFILE 0920 050, 51, 52, 53:

A number of quartz veins, stockworks and silicified fault zones in steeply dipping, northeasterly striking faults in Eocene volcanic rocks contain small, high-

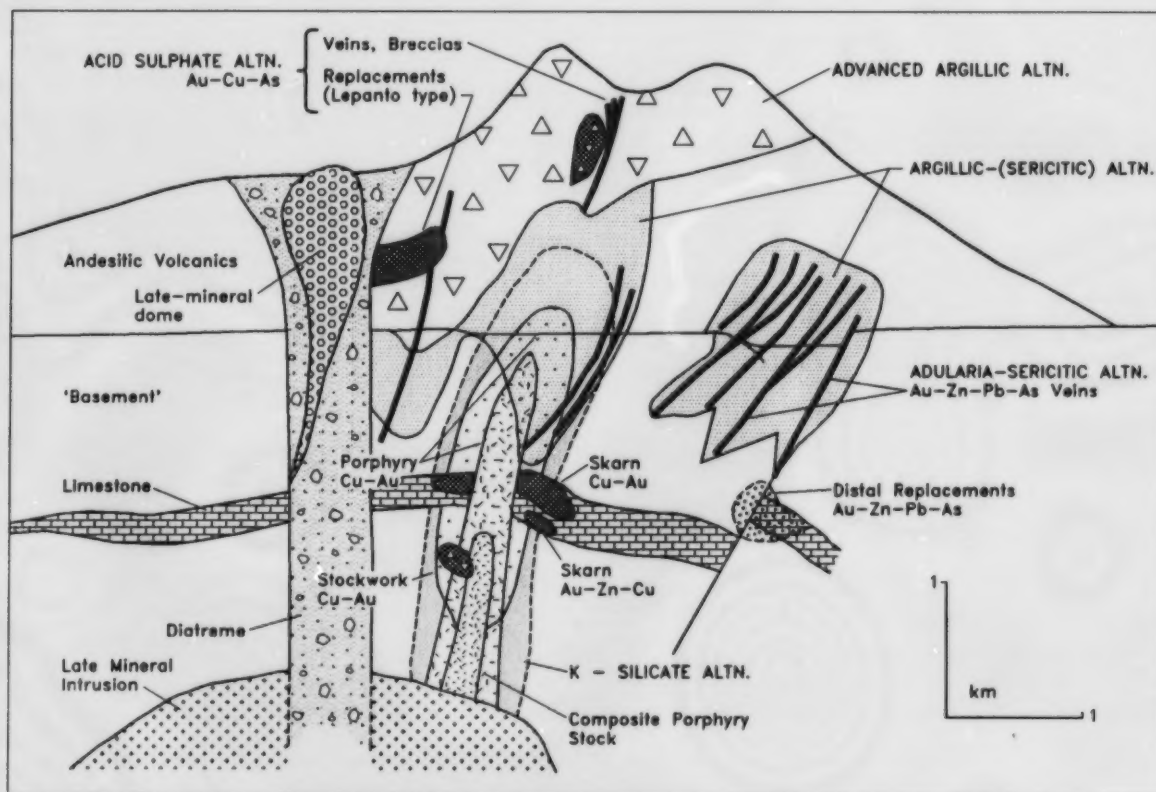


Figure 7-17. Mineralization in volcano-plutonic arc environments, from Sillitoe (1989, 1991a). The presence in any one deposit of all styles of mineralization is not implied. Environments depicted are transitional upwards from porphyry copper-type to epithermal. Most mineralization typically takes place at depths 1 to 3 km below the paleosurface.

grade ore shoots. The hostrocks form a well bedded, relatively flat-lying succession of calcalkalic predominantly andesitic tuffs and flows with intercalated rhyolite members. Only two of the dozen or so known vein systems, the Number 1 and Number 2 veins, have been mined. The quartz veins and silicified breccia zones are up to 3 metres in width and have open, vuggy structures; ore minerals are disseminated sparsely throughout. The ores contain native gold and silver, electrum, silver selenides, and rare silver sulphosalts along with minor pyrite and rare tetrahedrite, chalcopyrite, sphalerite and galena. Alteration envelopes around the veins in andesitic rocks form narrow bands with sericite and potassium-feldspar within a broader zone of propylitic alteration. In the rhyolites, narrow alteration envelopes with sericite and kaolinite pass outward into broad zones of intermediate argillic alteration.

A partly vented, Eocene or younger (Faulkner, 1986) geothermal system channeled by open fault structures gave rise to the bonanza-type gold-silver ores. Hydrothermal fluids were derived from meteoric, low-salinity solutions and mineralization took place at postulated depths of 0.5 to 1.1 kilometres (Vivian et al., 1987).

■ **Mount Washington — Domineer deposit — MINFILE 092F 116:**

The deposit lies about 400 metres to the south of the Eocene/Oligocene Mount Washington porphyry-type, breccia-hosted copper deposit. Mineralization forms a sub-horizontal tabular zone containing lenses and stockworks of auriferous quartz-pyrite-arsenopyrite. The zone occupies one of several flat-lying fracture and breccia structures that postdate the Tertiary intrusions and volcanic rocks and may represent either thrust faults or decollements.

A zone, 2 to 5 metres thick, of hydrothermal brecciation with enveloping kaolinite alteration lies in the centre of the mineralized body. The breccia consists of angular clasts of altered wallrock in a matrix of quartz and sulphide minerals. Locally the sulphides completely surround the clasts and have a banded nature. Outward from the strongly altered and mineralized core zone, the quartz-sulphide stockwork decreases in intensity; alteration, mainly by chlorite, becomes dominant and is restricted to vein selvages. In addition to the main minerals pyrite and arsenopyrite, small amounts of chalcopyrite, covellite, sphalerite, galena, bornite, tennantite, chalcocite, tellurides, realgar and orpiment are present. Pyrrhotite, magnetite and molybdenite are nearby but are probably unrelated to gold mineralization.

■ **Vault — MINFILE 082ESW 173:**

Mineralization is hosted by Eocene trachytic volcanic rocks and volcanoclastics of the Marama Formation. An westerly-trending resistant ridge is underlain by grey chacedonic quartz stockworks and fracture fillings. Pyrite forms vein selvages and small veinlets throughout the silicified zone. This is one of

a number of mineralized zones related to graben development in the Tertiary alkalic rocks of the Okanogan volcanic belt.

SUMMARY

Cordilleran deposit models and studies of mineralizing processes have advanced significantly the understanding of epithermal systems and their related deposits in recent years. The wide variety of deposits and their complex inter-relationships are becoming increasingly evident. Major advances have come from studies of hot spring, geothermal and deeper hydrothermal systems in continental, continent-margin, island arc and back-arc geological environments. Some of the more illuminating studies that provide useful comparisons for northern Cordilleran geologists are those by Sillitoe (1989, 1991a, 1991b). He describes the relationships between magmatic bodies and gold deposits based on his studies of the richly-mineralized, young volcanic island arcs of the western Pacific margin and Chilean Andes. Sillitoe's elegant summary is depicted on Figure 7-17. The diagram serves to illustrate the relationships of the possible ore types developed in volcano-plutonic island arcs, notably those in which porphyry copper-gold deposits are present. A somewhat generalized model for Cordilleran epithermal deposits by Panteleyev (1986), is included for comparison (Figure 7-18). It represents a dated but locally developed perspective of Cordilleran mineral deposit inter-relationships, with emphasis on depth-zoning.

As summarized by White and Hedenquist (1990) and Foster (1990): The type and style of epithermal mineralization (by definition) are related to hydrothermal activity at shallow crustal levels. It takes place in different tectonic, igneous and structural settings in which there are (both spatial and temporal) variations in district-wide, as well as local, deposit-scale geology, pressure and temperature conditions during mineralization/alteration, hydrology, fluid chemistry and changes in hydrothermal activity. Geology determines structure, stratigraphy and intrusive activity which, through time, determine the permeability and reactivity of hostrocks for mineralization. Tectonically influenced structural events, coupled with hydrothermal fracturing, commonly cause changes in permeability and hydraulic gradients during mineralization. Pressure and temperature control fluid boiling, phase separation within fluids and the local influence of steam-heated waters. Hydrology determined by the relationship between permeability and topography, governs fluid flow, mixing, discharge and recharge. Chemistry of the fluids determines their metal-carrying capacity and manner of fluid-rock interactions (alteration).

The two major types of epithermal deposits commonly recognized on the basis of their mineralogy — adularia-sericite (low sulphidation) and alunite-kaolinite (acid-sulphate, high sulphidation), are

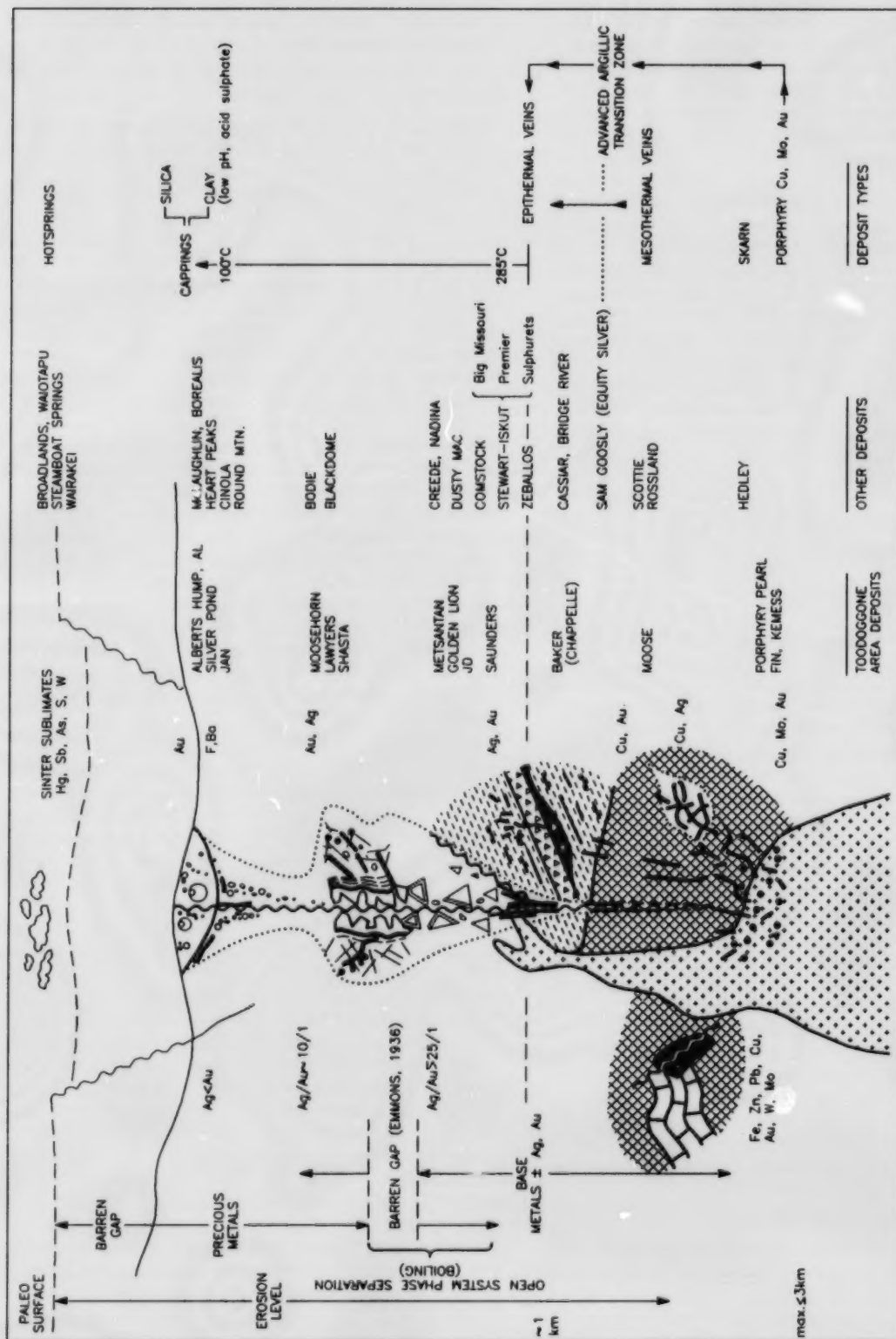


Figure 7-18. British Columbia epithermal model, based on studies of Jurassic epithermal deposits in the Toodoggone River area by A. Panteleyev and T. G. Schroeter (Panteleyev, 1986). The model infers that a continuum exists from porphyry copper and skarn through transitional deposits, to epithermal veins, and hot spring discharge sites. No distinction has been drawn between adularia-sericite-type deposits with near-surface argillic/advanced argillic alteration related to steam-heated, acid leaching as opposed to alunite-kaolinite high-sulphidation-type deposits. For a detailed discussion see Diakow et al. (1991).

derived from distinct geothermal systems as described by Henley and Ellis (1983). The former are associated with meteoric-source, near-neutral chloride hydrothermal systems in structurally extended, generally silicic volcanic terrains. The latter develop in andesitic-volcanic regions, commonly marked by belts of stratovolcanoes, from largely magmatic fluid sources. Their flow regimes are characterized by greater lateral flow of fluids, generally with highly acidic compositions. Epithermal deposits and their related porphyry copper-type (and possibly Kuroko-type) deposits are integral components of volcano-plutonic island arc and back-arc environments. Transitions in mineralization style can be seen upwards from stockwork and disseminated copper and/or gold deposits in intrusions (for example, Marte and El Lobo deposits, Chile, Vila and Sillitoe, 1991; Vila *et al.*, 1991) into either acid-sulphate or adularia-sericite (and locally small zones of related acid-sulphate alteration) of precious and base metal deposits near the paleosurface (Sillitoe, 1991b; Sillitoe and Camus, 1991). Manifestations of active or extinct geothermal activity at surface are the zones of distinctive hydrothermal alteration that overlie the deeper geothermal systems, most notably argillic/advanced argillic zones, silica caps, silica sinters and phreatic or phreatomagmatic (hydrothermal) breccia bodies.

Notable reviews of circum-Pacific epithermal environments and styles of mineralization by White and Hedenquist (1990), Henley (1991) and Sillitoe and Camus (1991) offer discussions of their variations and causes and, most importantly, provide guidelines for exploration. A perspective on applications of rock-geochemistry is provided by Clarke and Govett (1990) and discussions of geophysical characteristics of epithermal systems are offered by Allis (1990) and Irvine and Smith (1990).

ACKNOWLEDGMENTS

This discussion is an outgrowth from part of a short course initiated and coordinated by W.J. McMillan and presented at the Geological/Mineralogical Association of Canada annual meeting in Vancouver, 1990. Much of the above discussion has evolved from Ministry work in the Toodoggone area and ensuing discussions and insights shared with me by Tom G. Schroeter and Larry J. Diakow. Recent support by the Ministry and IUGS/UNESCO for travel in Chile and Bolivia in the company of Dick Henley, Dick Sillitoe, Skip Cunningham and others, as well as participation in epithermal workshops with them have eclipsed, collectively, even the best graduate courses and seminars that I have attended in the past. A considerable part of the above discussion is derived from and influenced by lecture presentations by Henley and Sillitoe but any errors, misrepresentations or deficiencies are my own.

I thank Anthony B. Christie for the use of some of his illustrations and information about geothermal

systems in New Zealand. Shaun Pattenden prepared a number of the figures used in the short course notes and lecture presentations. The illustrations, included here, have been produced by Pierino Chicorelli and Martin Taylor.

John M. Newell reviewed the Short Course Notes from which this paper is derived and edited the early manuscript. John F. H. Thompson and Richard W. Henley provided generous comments and constructive criticism of a draft version of this report.

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AN OVERVIEW OF SKARN DEPOSITS

by G. E. Ray and I. C. L. Webster

INTRODUCTION

This paper provides an overview of skarn deposits. It follows a format used by Edwards and Atkinson (1986), but draws largely on the work of Burt (1977), Einaudi *et al.* (1981), Einaudi and Burt (1982), Kwak (1987), Meinert (1988, 1989), Ettlinger and Ray (1989), Ray *et al.* (1987, 1988, 1990) and Theodore *et al.* (1991). An historical bibliography of skarn deposits between 1841 and 1970 has been given by Burt (1982); he notes that some observations and theories currently in vogue were originally suggested by geologists over 100 years ago.

The characteristics, alteration assemblages, tectonic setting and distribution of the various subclasses of skarn deposits are examined, particularly where they relate to examples in British Columbia. Special emphasis is directed towards calcic skarns and the characteristics, exploration criteria and potential of gold and precious metal enriched (PME) skarns in the province and elsewhere in the North American Cordillera.

CLASSIFICATION

Some skarn terminology is contentious and confusing, and reviews have been given by Burt (1977, 1982), and Einaudi and Burt (1982). The term skarn describes coarse-grained calcium or magnesian silicate alteration, commonly rich in Fe, Al, and possibly Mn, formed at relatively high temperatures by the replacement of original, often carbonate-rich rocks. Skarn may form by any of the following processes:

- Isochemical recrystallization of calcareous rocks as a result of regional metamorphism or local thermal metamorphism, (NOTE: Some geologists do not agree this represents skarn although high temperature calcsilicate alteration of this type is skarn *sensu strictu*).
- Localized metasomatic reaction between different lithologies, such as between argillite and limestone (**reaction skarn**).
- Infiltration metasomatism involving hydrothermal fluids of either magmatic or metamorphic origin (**infiltration skarn**).

Mineralization may occur with any combination of these processes, although most of the world's major skarn deposits were formed by the infiltration of magmatic hydrothermal fluids. Alteration resulting from the fluids overprints the genetically related intrusion to produce **endoskarn** as well as the adjacent sedimentary country rocks to form **exoskarn**. Fine-grained dense hornfels and skarn-like rocks of

uncertain origin, containing garnet or pyroxene assemblages, have been termed **skarnoid**; skarnoid can develop either locally, such as on the margins of a skarn envelope, or on a district-wide scale by regional metamorphism.

Most of the world's economic skarn deposits occur in exoskarn (Einaudi and Burt, 1982), although in some instances skarn alteration may be so intense that the original protolith is unrecognizable. While alteration commonly develops close to the related intrusion to form proximal skarn, the fluids may migrate considerable distances along structures, lithological contacts or bedding planes to form **distal skarns** whose parent source is unknown.

Based on alteration assemblages, skarns are separable into two broad classes: **magnesian skarns**, where the replacement of dolomite results in assemblages containing olivine, phlogopite, serpentine, spinel, magnesium-rich clinopyroxene, orthopyroxene, pargasite and humite group minerals and **calcic skarns**, where the replacement of limestone or other calcareous rocks produces assemblages dominated by garnet, clinopyroxene and wollastonite. However, skarns do not always form in carbonate-bearing rocks and may occur in calcium-rich volcanics and tuffs. Since a skarn is defined by its gangue mineralogy, it is not necessarily mineralized and many skarns are barren.

Metal deposits associated with skarn gangue are termed **skarn deposits** (Burt, 1972, 1977) and, on the basis of the dominant economic metal, at least seven major subclasses of skarn deposit are recognized: iron, copper, molybdenum, tungsten, zinc-lead, tin and gold skarns (Knopf, 1942; Einaudi *et al.*, 1981; Orris *et al.*, 1987; Ray *et al.*, 1987, 1990; Meinert, 1988, 1989; Ettlinger and Ray, 1989; Theodore *et al.*, 1991).

Knopf (1942) suggested the existence of four other subclasses dominated by graphite, barium, platinum and cerium, although no major economic skarn deposits of these types are recorded. Some magnesian skarn deposits in the U.S.S.R. have been mined for coarse phlogopite and various borate minerals such as kotoite and ludwigite (Pertsev, 1971; 1991). In addition, some skarns are radioactive and are enriched in uranium, thorium and rare-earth elements (REE); examples occur in the Grenville Province of Ontario and Quebec (Shaw *et al.*, 1963; Lentz, 1991). These are spatially and genetically related to radioactive pegmatites and veins, some of which were mined for uranium. They contain calcic pyroxene, as well as variable amounts of apatite, scapolite, phlogopite, fluorite, pyrite, pyrrhotite,

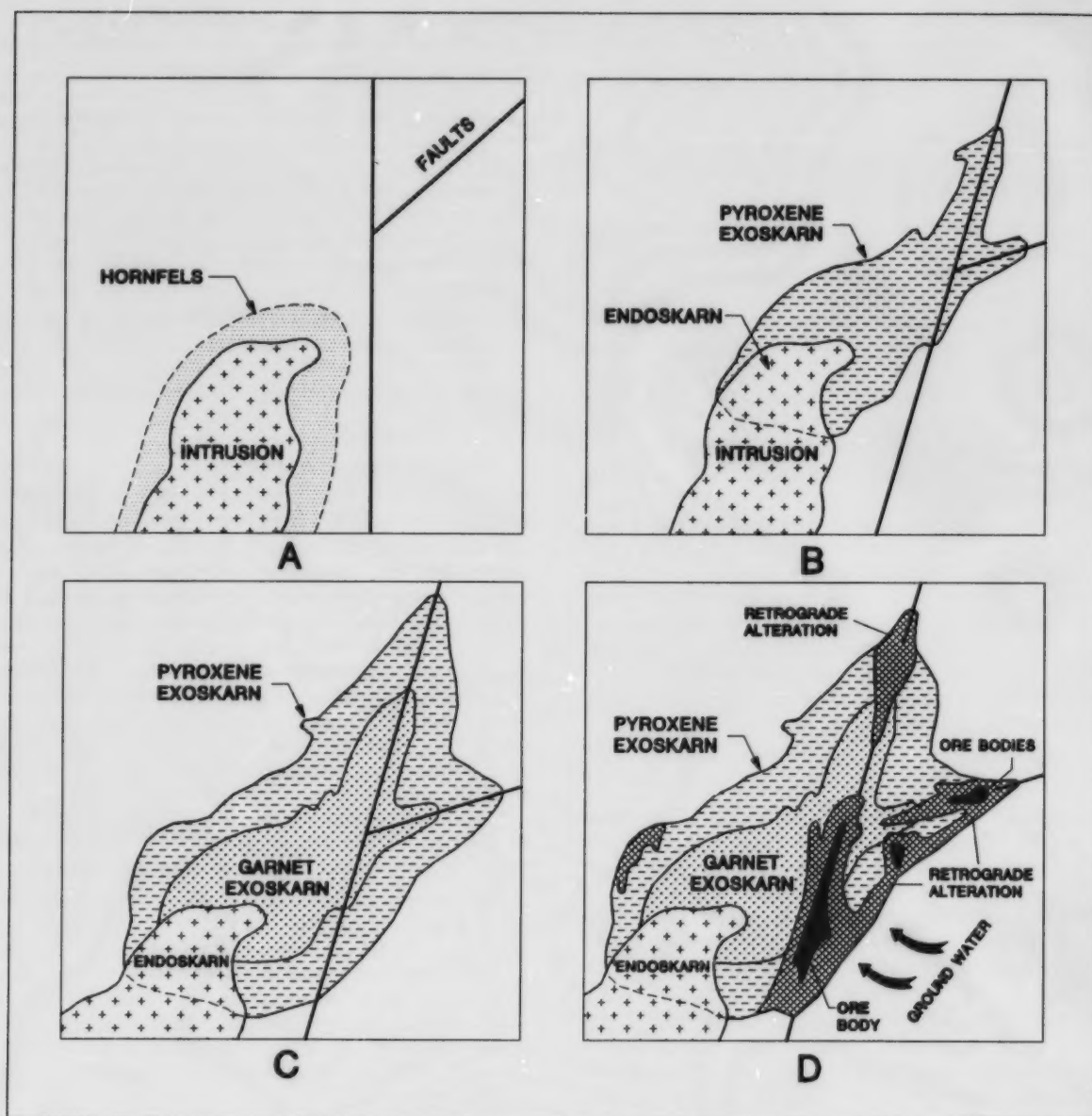


Figure 8-1. Schematic evolution of a calcic skarn deposit:

- Intrusion of magma into carbonate-rich sequence and formation of contact hornfels (hornfels not shown in B, C or D).
- Infiltration of hydrothermal fluids to produce endoskarn and pyroxene-rich exoskarn.
- Continued infiltration with progressive expansion of exoskarn envelope and development of proximal garnet-rich exoskarn. Skarn controlled partly by lithologies (e.g., limestone beds locally replaced by garnetite), bedding planes and fractures. Some mineralization may take place late in this stage.
- Hydrothermal system wanes and cools accompanied by retrograde overprinting. During this stage metals may be introduced or scavenged and redeposited to form economic orebodies. The structural/lithological controls and influence of meteoric water may result in irregularly distributed orebodies that are notoriously difficult to delineate in skarn.

molybdenite, uraninite, thorinite, uranothorite and allanite (Lentz, 1991).

Some copper and iron skarns, and to a lesser degree zinc-lead and tungsten skarns, may be enriched in gold; in such precious metal enriched (PME) skarns this metal may be an important economic byproduct. Although all the skarn deposit subclasses occur in both magnesian and calcic skarns, copper, tungsten and zinc-lead deposits are less common in magnesian skarns (Einaudi *et al.*, 1981). The overwhelming majority of gold skarn deposits are developed in calcic skarns.

EVOLUTIONARY MODEL OF SKARN FORMATION

Skarn deposits are generally hosted within zones or halos of exoskarn alteration with morphologies that vary from stratiform, to subcircular, to vein-like, and sharply discordant. The amount of exoskarn developed ranges from narrow zones up to large envelopes that involved the generation of several cubic kilometres of skarn alteration. The associated mineralization is often volumetrically small compared to the total size of the skarn. Formation of the envelopes is an evolving, complex process, but the following paragenetic stages (Figure 8-1) are common to many infiltration calcic skarns:

1. Magmatic intrusion into relatively cool hostrocks leading to the production of an isochemical, contact metamorphic calcsilicate or biotite-rich hornfels.
2. Infiltration of magmatic hydrothermal fluids into the surrounding country rocks, resulting in multiple stages of metasomatic garnet-pyroxene $\pm$ amphibole prograde skarn assemblages. A skarn halo is produced which continues to expand until the hydrothermal system wanes. The margins of this metasomatic envelope may pass out into a fine grained pyroxene-rich hornfels-like rock or skarnoid.
3. Retrograde alteration of the prograde skarn assemblages as the envelope cools. This results in the formation of lower temperature hydrous phases such as chlorite, epidote, amphibole, ilvaite or, more rarely, scapolite. Sometimes this stage is associated with the introduction or redistribution of mineralization.

Formation of an isochemical calcsilicate hornfels either during Stage 1 or Stage 2 often renders the wallrocks receptive to brittle fracturing which increases permeability for the later skarn-forming fluids. The fluids continue to infiltrate the surrounding hostrocks under pressure, causing the skarn envelope to steadily grow in size. Passage of the fluids is controlled by rock permeability, fractures, fold structures and lithological contacts, all of which influence the ultimate morphology of the skarn (Figure 8-1).

In most calcic skarns, pyroxene is the first dominant mineral to develop in Stage 2 (Figure 8-1B) and it generally continues to crystallize throughout the entire phase of prograde skarn formation. Garnet has a shorter period of crystallization and it generally postdates the appearance of pyroxene (Plate 8-1). Thus, the generalized sequence of prograde crystallization in many skarns is: (1) pyroxene, (2) pyroxene and garnet, (3) pyroxene. In many copper and some gold skarns the prograde alteration may initially involve potassic metasomatism marked by crystallization of biotite and orthoclase; this potassic alteration postdates the Stage 1 contact metamorphic hornfels and predates the pyroxene-garnet assemblages.

Mineralization occurs either late in Stage 2 or during the Stage 3 retrograde alteration as temperatures decline (Figure 8-1D). In some calcic iron skarns, magnetite is introduced relatively early and it can be overgrown by garnet. However, retrogression is important in many skarn deposits since any low grade mineralization introduced during the prograde phase may be scavenged and redeposited in economic ore zones. This late upgrading takes place in many tungsten skarns (Dick, 1979; Dick and Hodgson, 1982), and the importance of retrograde activity in developing an ore grade skarn deposit has been emphasized by Meinert (1986).

The Stage 3 generation of retrograde hydrous minerals occurs during the final cooling process, sometimes due to interaction with meteoric waters (Figure 8-1D). The degree of retrograde alteration varies enormously in skarns. Intense alteration is common in many iron and tungsten skarns and in copper skarns related to copper porphyry deposits. Propylitic alteration is rare in the Hedley gold skarns, although the intense scapolitization in these deposits may represent a retrograde event.

Magnesian skarns often undergo similar evolutionary stages except that the skarn silicates can start crystallizing during the Stage 1, high temperature magmatic phase (Pertsev, 1991). Stages 1 and 2 in magnesian skarns typically result in the growth of olivine, spinel, phlogopite, pyroxene, pargasite and calcic plagioclase. Stage 3 leads to the overprinting of these minerals by serpentine, talc and amphibole; gangue minerals in magnesian skarns tend to be rich in alkalis, and contain hydroxyl and fluorine (Pertsev, 1991).

Based largely on spatial relationships, geologists have long suggested that the intrusions were the primary source of both the skarn-forming fluids and the metals in many base and ferrous metal skarns (e.g., Rath, 1868; Packard, 1895; see Burt, 1982). Likewise, at the Hedley skarns, gold is also believed to have originated from magmatic fluids (Dolmage and Brown, 1945) that were saline and relatively high temperature (Ettlinger *et al.*, in press). Mineralization can be deposited either close to the intru-

sions, as in many molybdenum skarns, or more distal as in many gold and zinc-lead skarns.

The chemistry and mineralogy of both the prograde assemblages and the skarn mineralization are influenced by a number of factors including: (1) lithology of the original hostrocks, (2) depth of formation and (3) composition of the intrusion and the hydrothermal fluids. Dolomitic rocks are favourable hosts for some iron and tin skarns but tend to inhibit the development of tungsten skarns. Calcareous siltstones are commonly altered to pyroxene-rich assemblages whereas impure, permeable limestone may lead to the formation of massive garnetite. Some skarns, particularly calcic iron skarns, may form in non-carbonate-bearing volcanic or intrusive rocks.

The oxidizing or reducing capacity of the hostrocks, related to the presence of carbon, hematite or gypsum, may also influence the skarn mineralogy and metal chemistry. A reduced hostrock tends to result in high pyrrhotite:pyrite ratios, magnetite rather than hematite, and low $\text{Fe}_2\text{O}_3:\text{FeO}$ ratios in the silicates; it may also influence garnet:pyroxene ratios in the exoskarn.

Depth of formation also controls development of a skarn as well as its morphology, metal content, chemistry, oxidation state and intensity of alteration (e.g., Casquet and Tomos, 1991). Increased metamorphism, ductile deformation, higher temperature

mineral assemblages and relatively reduced states are more pronounced in deeper level skarns. At shallower depths, skarns are increasingly controlled by brittle structures, have more oxidized mineral assemblages and are more readily retrograde-altered by ground water.

The paragenetic sequences in Stages 1 to 3 result in many calcic and magnesian skarns possessing both spatial and temporal mineralogical zoning patterns that can assist mineral exploration (Burt, 1974). Depending on the skarn deposit subclass and its environment of formation, these zones can be highly variable. However, in calcic skarns a generalized zoning from the intrusion to unaltered country rocks is often as follows: (1) endoskarn, (2) garnet-dominant exoskarn, (3) pyroxene-dominant exoskarn, (4) vesuvianite, wollastonite, bustamite or rhodonite-bearing skarn with abundant carbonate, (5) marble, with or without silicification, (6) unaltered wallrock. If the fluids are undersaturated in silica, or too low in temperature, the wollastonite-rich zone may not be developed. In magnesian skarns, the most common mineral zoning developed between granite and dolomite is: (1) endoskarn, (2) pyroxene and plagioclase-rich exoskarn, (3) olivine and spinel-rich exoskarn, (4) dolomite (Pertsev, 1991).

The widths of individual zones are highly variable and some zones may be absent locally. Since the

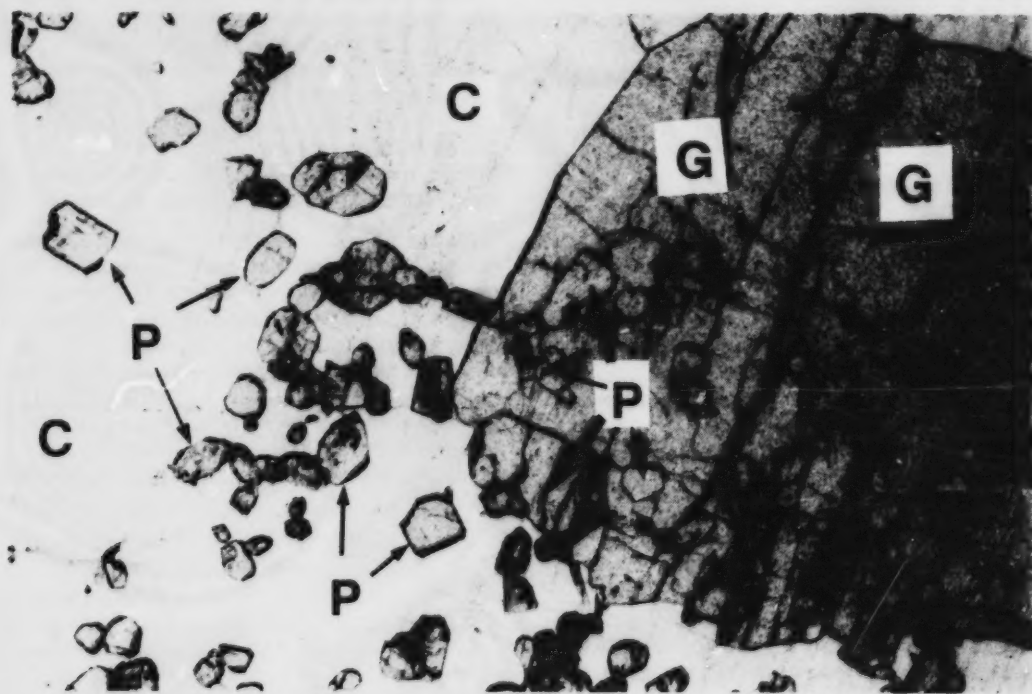


Plate 8-1. Photomicrograph (PPL) showing early, subhedral hedenbergitic pyroxene (P) overgrown by andraditic garnet (G) and carbonate (C). Good Hope mine gold skarn, Hedley, B.C. Field of view is 3 millimetres wide.

garnets and pyroxenes closer to the intrusion have generally undergone a longer period of growth than those on the skarn margin, there tends to be an increase in crystal size toward the intrusion. Also the composition of the pyroxenes and garnets may progressively change across a skarn, and both chemical and optical zoning may be present within individual garnet and pyroxene crystals; this commonly reflects a progressive change in fluid composition, pH, sulphur fugacity or oxidation state as the mineral crystallized. Thus, knowledge of chemical zoning in the crystal may reveal details on the evolution and changing conditions of skarn development. Studies on metasomatic or mineralogical zoning in skarn deposits include those by Burt (1974), Atkinson and Einaudi (1978), Catlin (1984) and Newberry (1987, 1991); an example of compositional and optical zoning in a garnet crystal from the Nickel Plate gold skarn is shown in Plate 8-2 and Figure 8-2.

Fluid inclusion and stable isotope studies (quoted by Einaudi *et al.*, 1981; Kwak, 1986) indicate that the ore solutions in infiltration skarn, compared to

those in metamorphic skarn or mineralized veins, are more saline, have higher CaCl_2 contents and form at higher temperatures. In magnesian skarns, silicate minerals crystallizing during the early, magmatic stage of skarn formation may develop at temperatures of between 700 and 1100°C (Pertsev, 1991). Prograde calcic skarn formation generally occurs at temperatures between 400 and 650°C, although both temperatures and salinities tend to decrease away from the fluid source both in time and space (Kwak, 1986). Higher temperatures characterize skarns formed at deeper levels (1-3 kb) such as some tungsten and tin skarns. The metasomatic fluids commonly have a low CO_2 content (X_{CO_2} less than 0.1) and moderate to high salinities (10 to 50% NaCl equivalent). Boiling appears to be more characteristic of skarns formed in shallower environments. Kwak (1986) notes that the fluid inclusions in skarns adjacent to potassium-rich granitoids have high KCl contents whereas those formed close to calcic intrusions are relatively enriched in NaCl.

Our slight knowledge of fluid inclusions and stable isotopes in gold skarns has been summarized by Theodore *et al.* (1991) and Theodore and Hammarstrom (1991). Boiling Na-Ca-Fe brines, containing up to 70 weight per cent NaCl equivalent, circulated in the Battle Mountain gold-bearing skarns of Nevada, and the prograde skarn developed at a temperature of about 475°C (Theodore and Hammarstrom, 1991). At the Nickel Plate deposit, garnet and pyroxene crystallized at temperatures (pressure corrected) averaging 460 to 480°C although temperatures locally exceeded 700°C (Ettlinger *et al.*, in press). The salinity of fluid inclusions in garnet at Nickel Plate averaged 18 per cent NaCl equivalent.

Commonly, both mineralization and late retrograde alteration in skarn are structurally and stratigraphically controlled (Figure 8-1D). They may



Plate 8-2. Photomicrograph (X polars) showing euhedral exoskarn garnet with isotropic cores and birefringent margins. Nickel Plate mine gold skarn, Hedley, B.C. Field of view is 3 millimetres top to bottom.

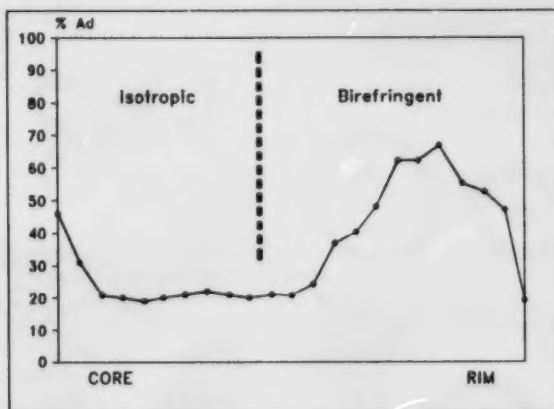


Figure 8-2. Variation in composition across a single garnet crystal from the Nickel Plate gold skarn. NOTE: The aluminous, grossular-rich, isotropic cores, and more iron-rich, andraditic, birefringent margins. Microprobe traverse with 23 analyses on Sample GR 672A.

overprint any of the various mineralogical zones of prograde skarn, which often causes additional difficulties in the geological mapping and paragenetic interpretation of individual skarn deposits.

To summarize, the complexity of skarn morphology and mineralogy is partly caused by hostrock lithology and depth of emplacement, as well as the chemistry of the hydrothermal fluids which may change as the system evolves. As the exoskarn envelope enlarges, early prograde minerals that were developed close to the intrusion may be overgrown by the same minerals of progressively different composition or replaced by new minerals. A steady overgrowing of minerals under changing conditions of oxidation, sulphidation, temperature and fluid chemistry may result in compositional zoning in garnet, pyroxene and amphibole crystals. Additional complexity occurs in the skarn envelope with subsequent overprinting by hydrous phase retrograde alteration and mineralization, both of which may be partly structurally controlled. This often results in irregular and complex orebodies that are difficult to delineate and explore.

DISTRIBUTION, AGE AND TECTONIC SETTING

Skarn deposits throughout the world range in age from Precambrian to Late Tertiary, although most major deposits are of Mesozoic to Cenozoic age. However, a few important skarns are Paleozoic. These include the King Island tungsten and tin deposits of Tasmania (Danielson, 1975; Kwak and White, 1982; Kwak, 1987), and the copper skarns of the Mines Gaspé area in Quebec (Allcock, 1982; Shelton, 1983). The older ages of the tungsten and tin skarns commonly reflects their relatively deep level of formation (Einaudi *et al.*, 1981).

Some major Paleozoic gold and PME skarns also occur in eastern Australia and what was formerly the central U.S.S.R. and these appear to be spatially and temporally associated with Paleozoic porphyry copper belts of those regions. Examples include the Veselyi deposit in the Siniukhinskoe district of Siberia (Vakhrushev and Tsimbalist, 1967; Ettlinger and Meinert, 1991) and the Red Dome deposit in Queensland (Torrey *et al.*, 1986; Ewers and Sun, 1988).

Skarn deposits are distributed worldwide, and some of the major deposits are listed in Tables 8-1 and 8-2. Most major iron, gold, tungsten, molybdenum and zinc-lead skarns and some copper skarns are found within the Phanerozoic orogenic belts comprising either oceanic island arcs or arcs formed adjacent to continental margins. However, tin skarns and some major copper skarns are developed in continental crust. Some deposits, particularly iron, gold, copper and molybdenum skarns commonly develop in districts that also contain other types of mineralization such as copper porphyry deposits, mesothermal veins and epithermal systems.

The general tectonic setting of all skarn deposit subclasses, except gold skarns, has been outlined by Einaudi *et al.* (1981), Einaudi and Burt, (1982), and Meinert, (1983), and the idealized tectonic model for these are shown in Figure 8-3A. In addition, the fore-arc, rifted back-arc and simatic continental margin arc environments favourable for gold skarns, as determined from British Columbian examples (Ray *et al.*, 1990), are presented in Figure 8-3B, C and D.

TABLE 8-1

Major Fe, W, Cu, Zn-Pb, Mo and Sn Skarns of the World

Iron skarns (calcic)

- Perschansk, Sverdlovsk, U.S.S.R. (173 m.t)
- Dashkesan, U.S.S.R. (187 m.t)
- Tasu, B.C., Canada, (20.8 m.t)
- Shinyama, Kamaishi, Japan, (>10 m.t)
- Cornwall, Pa. U.S.A. (>100 m.t)
- Daiquiri, Cuba, (>10 m.t)

Iron skarns (magnesian)

- Sheregesh, Gornaya Shoriya, U.S.S.R. (234 m.t)
- Teya, Krasnoyarsk, U.S.S.R. (144 m.t)
- Eagle Mountain, California, U.S.A. (>50 m.t)

Tungsten skarns (reduced)

- Mactung, NWT, Canada, (>30 m.t)
- Cantung, NWT, Canada, (>6 m.t)
- Pine Creek, California, U.S.A. (>6 m.t)
- Sangdong, Korea, (>10 m.t)

Tungsten skarns (oxidized)

- King Island, Tasmania, Australia, (14 m.t.)
- Osgood Mountains, Nevada, U.S.A. (1.4 m.t)

Copper skarns (associated with porphyry copper deposits)

- Twin Buttes, Arizona, U.S.A. (400 m.t)
- Bingham, Utah, U.S.A. (>100 m.t)
- OK Tedi, Papua New Guinea, (40 m.t)

Copper skarns (associated with barren stocks)

- Rosita, Nicaragua, (3.4 m.t)
- Merme, Haiti, (>1.2 m.t)
- Mason Valley, Nevada, U.S.A. (1.5 m.t)
- Phoenix, B.C. Canada, (26.9 m.t)

Zinc-Lead skarns

- Yeonhwa, Korea, (3.6 m.t)
- Groundhog, New Mexico, U.S.A. (3 m.t)
- Santa Eulalia, Mexico, (32 m.t)
- Stri Trg, Yugoslavia, (13.7 m.t)
- El Mochito, Honduras, (8 m.t)

Molybdenum skarns

- Mount Tennyson, N.S.W. Australia, (>1.5 m.t)
- Yangchiachangtze, China, (7 m.t)
- Azegour, Morocco, (>130 000 tonnes)

Tin skarns (calcic)

- Moina, Tasmania, Australia, (30 m.t).
- Lost River, Alaska, U.S.A. (3 m.t)

Tin skarns (magnesian)

- Renison Bell, Tasmania, Australia, (>7 m.t)
- Mt. Bischoff, Tasmania, Australia (5.5 m.t)

Gold and PME skarns

See Table 8-2.

Deposit size, in millions of tonnes, in brackets; data from Einaudi *et al.* 1981; Einaudi and Burt, 1982; Edwards and Atkinson, 1986.
m.t. = million tonnes.

TABLE 8-2

Selected Gold and PME-Skarns of the World (see Figure 8-8)

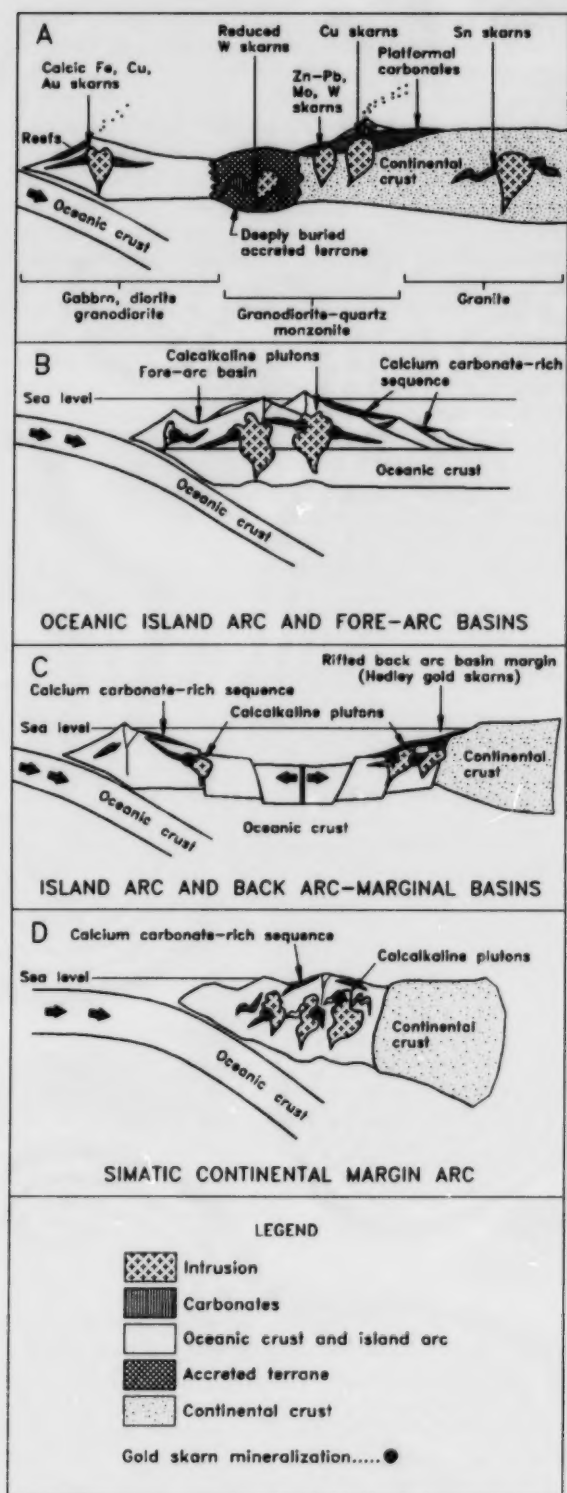
No. in Fig. 8-8	Deposit	Size (tonnes)	Au (g/t)	Ag (g/t)	Cu (%)
1	Nickel Plate and Hedley-Mascot, B.C. (underground)	3 600 000	14.0	1.4	0.1
1	Nickel Plate, Hedley, B.C. (open pit)	8 250 000	2.75	3.0**	0.1
2	Phoenix, B.C.	26 956 000	1.1	7.1	0.9
2	Buckhorn Mountain, Washington, U.S.A.	6 700 000	3.5	NA	NA
3	Texada Island, B.C. (Cu-Au skarns)	310 000	2.4	16.0	3.0
3	Old Sport, B.C.	2 600 000	1.46	4.4	1.55
4	Zackly, Alaska, U.S.A.	1 200 000	5.5	30.0	2.7
4	Nixon Fork, Alaska, U.S.A.	NA	NA	NA	NA
5	Fortitude (Lower), Nevada, U.S.A.	5 100 000	10.4	27.8	0.2
5	Tomboy Minnie, Nevada, U.S.A.	3 500 000	3.1	9.6	0.03
5	McCoy, Nevada, U.S.A.	14 500 000	1.5	30	0.1
5	Mt. Hamilton, Nevada, U.S.A.	7 000 000	1.7	17.1	NA
6	Carr Fork, Utah, U.S.A.	61 000 000	0.4	10.7	1.8
7	Cable, Montana, U.S.A.	1 000 000	6.0	5.0	3.0
7	Golden Curry, Montana, U.S.A.	930 000	8.5	4.2	0.33
7	Southern Cross, Montana, U.S.A.	400 000	13.0	16.0	0.1
8	Golfo de Oro, Mexico	5 000 000	4.5	10.0	NA
8	Concepcion del Oro, Mexico	15 000 000	1.7	NA	2.0
9	Rosita, Nicaragua	3 450 000	1.1	15.8	3.0
9	La Luz, Nicaragua	15 000 000	4.1	1.2	0.44
10	Browns Creek, Australia	400 000	8.7	10.0	0.4
10	Sheahen-Grants, Australia	1 520 000	4.5	NA	NA
11	Mount Biggendon, Australia	500 000	15.0	NA	NA
12	Red Dome, Australia	13 800 000	2.3	5.2	0.46
13	Bau, Malaysia	2 400 000	7.2	0.1	NA
14	Siana, Philippines	5 400 000	5.1	10.0	NA
14	Thanksgiving, Philippines	1 700 000	6.4	40.6	0.4
15	Rokuromi, Japan	80 000	8.0	2.0	NA
16	Suian, North Korea	530 000	13.0	4.9	NA
17	Tul Mi Chung, North Korea	400 000	12.0	NA	NA
18	Reicher Trost, Germany	10 000	20.0	0.1	NA
19	Siniukhinskoe, U.S.S.R.	NA	8.0	37.7	3.9
20	Salsigne, France***	1 500 000	13	33	0.15
21	Lebedskoe (Kaurchack), U.S.S.R.	120 000	4	NA	NA
22	Pagaran Siayu, Indonesia	110 000	5.6	2.5	0.2
23	Nabesna, Alaska, U.S.A.	80 000	25	NA	NA
24	Naica, Mexico	10 000 000	0.4	180	0.4
25	Huarcra, Peru	500 000	2.0	10	3.0
25	Katanga, Peru	2 000 000	6.1	46.5	3.5
26	Vieja, Columbia	450 000	1.0	35	1.7
26	El Sapo, Columbia	330 000	11.5	79.8	5.1
27	OK Tedi, Papua, New Guinea	40 000 000	1.6	NA	1.5
28	Marvel Loch (Savage Lode), Western Australia	3 280 000	3.0	0.59	NA

Data source for most deposits: Orris *et al.*, (1987), Ettlinger and Ray (1989), Theodore *et al.*, (1991). Data source for Siniukhinskoe: Ettlinger and Meinert (1991); for Nabesna: Wayland (1943); for Marvel Loch: Mueller (1991).

NA=values not available.

** Estimated silver grade.

*** There is some uncertainty whether Salsigne represents a skarn deposit (G.J. Orris, personal communication, 1989).



These clearly illustrate the strong influence that plate tectonic settings have on skarn ore chemistry.

Magnesian iron skarns are distributed worldwide in continental-margin orogenic belts, commonly within base-metal sulphide skarn districts where dolomites are present. Both gold and calcic iron skarns are characteristic of subduction-related oceanic island-arc terrains where they tend to be associated with dioritic intrusions derived from oceanic crust. However, most gold skarns form in more reduced environments than calcic iron skarns.

Most of the world's copper skarn deposits formed in continental crust where they are commonly related to porphyry copper systems; this type may locally contain important byproduct gold, silver and molybdenum. British Columbia contains the less common suite of calcic copper skarn, such as the Craigmont and Phoenix deposits (McNaughton, 1945; Morrison, 1980; Church, 1986), which occur in an island-arc setting.

Tungsten, calcic zinc-lead and base metal (Cu, Zn-Pb, Mo) sulphide skarns are characteristic of continental margin magmatic belts, while some tungsten skarns form in deeply buried, carbonate-bearing accreted terrains. Besides a deeper environment of formation, many tungsten skarns tend to form at higher temperatures, and in more reduced conditions than iron, copper or zinc-lead skarns. Calcic zinc-lead skarns often develop during the middle to late orogenic stages of a belt, and tend to occur along structural or lithological contacts, sometimes at considerable distances from the source plutons.

Tin skarns are associated with ilmenite-series granites of both I and S-types, and form either in the later stages of continental magmatic arc development or in relatively stable or incipiently rifted cratonic environments (Figure 8-3A). They are commonly characterized by greisenization and a geochemical association with fluorine and boron-bearing minerals (Burt, 1978; Kwak, 1987).

Figure 8-3. Idealized plate tectonic model for various calcic and magnesian skarn deposit subclasses:

- A. Oceanic island arc, accreted arc and continental crust (Au, Fe, Cu, Mo, W, Zn-Pb and Sn skarn deposits). Adapted after Meinert (1983).
- B. Island arc and forearc basin (gold and PME skarns, e.g., Iskut River area, northwest B.C.).
- C. Island arc and back arc-marginal basin (gold and PME skarns, e.g., Hedley camp, southern B.C.).
- D. Simatic continental margin arc (Fe, Cu, Au and PME skarns, e.g., Vancouver Island and Texada Island skarns, B.C.).

GENERAL CHARACTERISTICS

MINERALOGY

The predominant ore minerals for each skarn class are summarized in Table 8-3. Magnetite is the main ore mineral in iron skarns while chalcopyrite, scheelite, molybdenite and cassiterite are the principal economic minerals for copper, tungsten, molybdenum and tin skarns respectively. Zinc-lead skarns are characterized by sphalerite and galena, while in gold skarns the native gold is commonly associated with tellurides and generally occurs as microscopic inclusions in the sulphides.

The most common gangue sulphides in skarn are pyrrhotite and pyrite. Calcic iron skarn deposits may contain, in the magnetite ore, pyrite-pyrrhotite-chalcopyrite-rich pockets with some gold and cobaltite. Many gold skarns, such as those in the Hedley district, contain abundant arsenopyrite.

The main gangue minerals in calcic skarns are pyroxene and garnet with subordinate and variable amounts of amphibole, carbonate, epidote, chlorite and wollastonite. Garnet, pyroxene and amphibole are useful minerals in aiding classification as they are widely distributed and may exhibit systematic compositional variations (Table 8-4; Figure 8-4) that reflect the various skarn deposit subclasses (Zharikov, 1970; Burt, 1972; Einaudi *et al.*, 1981). Most skarn pyroxenes are diopside-hedenbergite solid solutions but an increased manganese content occurs in the pyroxenes of tungsten, zinc-lead and molybdenum skarns (Figure 8-4). A high manganese content in zinc-lead skarns, together with relatively lower temperatures and/or a higher X_{CO_2} content are responsible for the common occurrence of bustamite or rhodonite rather than wollastonite.

Garnets in skarn have a wide range of colour, and include both optically birefringent and isotropic varieties (Plate 8-2). With the exception of tungsten and tin skarns, most garnets are grossular-andradite solid solutions containing less than 20 mole per cent spessartine+almandine. Iron and gold skarns are characterized by very low manganese (<1 weight per cent MnO_2) grandite garnets and low manganese (<4 weight per cent MnO_2) iron-rich diopside-hedenbergitic pyroxenes (Figure 8-4). Many tin and tungsten skarns are relatively enriched in alumina resulting in the occurrence of vesuvianite with, or in place of, pyroxene or wollastonite (Einaudi and Burt, 1982). The amphiboles in tin and tungsten skarns also tend to be aluminous (hastingsite-hornblende), while those from copper, molybdenum, iron and gold skarns are more iron-rich in the tremolite-ferroactinolite series. Amphiboles from zinc-lead skarns are more manganese-rich and calcium-deficient (Meinert, 1983), while the chlorine-rich amphibole dashkesanite is described at the Dashkesan iron skarn in the Azerbaijan region, U.S.S.R. (Sokolov and Grigorev, 1977). Likewise,

some gold skarns in British Columbia contain chlorine-rich amphiboles (Ettlinger and Ray, 1989).

Some skarns replacing basaltic or pelitic rocks can have a distinctive silicate mineralogy, often due to the high Al:Si ratio in the altered hostrock; for example, some tin skarns hosted in basalts in Cornwall, England are associated with garnet-pyroxene assemblages rich in spinel and amphibole of sadanagaitic composition (van Marcke de Lummen and Verkaeren, 1985). Also present in these assemblages are tourmaline, axinite and vesuvianite.

ASSOCIATED INTRUSIONS

The igneous rocks associated with skarn deposits range in composition from gabbro to granite (Table 8-3; Figure 8-5A and 5B). In Table 8-5 are listed the major element chemical compositions of the intrusive rocks associated with each of the seven major subclasses of skarn deposits. Alkali versus silica and AFM plots (Figure 8-5C and 5D) illustrate that all the deposit subclasses are associated with subalkalic, calcalkaline intrusions. Two noted exceptions occur in British Columbia. One includes the iron and copper-gold skarns of the Merry Widow camp on Vancouver Island that are associated with gabbros and andesites of tholeiitic affinity (Ray and Webster, 1991). The other is the skarn-type alteration assemblages associated with some copper-gold porphyry deposits that are related to alkalic intrusions (*e.g.*, Hodgson *et al.*, 1976). Some iron skarns on Vancouver and Texada islands are associated with intrusions that locally contain abundant apatite.

Plots in Figures 8-5 and 8-6 demonstrate systematic geochemical variations, and the intrusive rocks associated with tin and gold skarns represent two chemically contrasting end members. Compared to the other skarn subclasses, the igneous rocks related to gold skarns (represented by the Hedley intrusions) contain the least silica (Figure 8-6A) and the most calcium, ferrous iron, total iron, magnesium and alumina (Figures 8-6B, 6C and 6D; Table 8-5). By contrast, those related to tin skarns have the highest silica content, as well as the lowest amounts of total iron, magnesium, alumina and calcium.

Intrusions related to tin, molybdenum, tungsten, and zinc-lead skarns generally have the highest total alkali content while the Hedley gold skarns are associated with intrusions that generally contain less than 5 per cent combined $\text{K}_2\text{O} + \text{Na}_2\text{O}$. Meinert (1983) notes no significant difference in the total alkali content of intrusions related to tungsten, molybdenum, zinc-lead and tin skarns, although the $\text{K}_2\text{O}:\text{Na}_2\text{O}$ ratios show some variation (Figures 8-5B and 8-6B). Plutons associated with iron and gold skarns tend to have very low $\text{K}_2\text{O}:\text{Na}_2\text{O}$ ratios (<0.5), those with tungsten, copper, and zinc-lead skarns have ratios averaging close to 1.0, while those related to molybdenum and tin skarns are characterized by higher

TABLE 8-3

Characteristics of Major Skarn Deposit Subclasses

Type	Tungsten (calcic)	Tin (calcic)	Tin (magnesian)	Copper (calcic)	Zinc-lead (calcic)
Metal association (minor metals)	W,Mo,Cu (Zn,Bi)	Sn,F (Be,W)	Sn,F (Be,B)	Cu (Mo,W,Zn)	Zn,Pb,Ag (Cu,W)
Tectonic setting	Continental margin Late orogenic	Continental margin Late to post-orogenic	Continental margin Late to post-orogenic	Continental margin Late orogenic	Continental margin Late orogenic
Associated intrusive rocks	Quartz diorite, quartz monzonite	Granite	Granite	Granodiorite to quartz monzonite	Granodiorite to granite, diorite to syenite; plutons commonly absent
Intrusive morphology	Batholiths	Stocks, batholiths	Stocks, batholiths	Stocks, dikes, breccia pipes	Large stocks, to dikes — if present
Intrusive alteration	Local mica, calcite, pyrite endoskarn	Greisen	Greisen	Local endoskarn, K-silicate, sericitic	Extensive endoskarn
Ore mineralogy	Scheelite, molybdenite, chalcopyrite pyrrhotite, pyrite	Cassiterite, arsenopyrite, stannite, pyrrhotite	Cassiterite, minor arsenopyrite, stannite, sphalerite, pyrrhotite	Chalcopyrite, bornite, pyrite, hematite, magnetite	Sphalerite, galena, chalcopyrite, arsenopyrite
Typical size (million tonnes)	0.1–2	0.1–3	1	1–100	0.2–3
Typical grade	0.7% WO ₃	0.1–0.7% Sn	1% Sn	1–2% Cu	9% Zn, 6% Pb, 170 g/t Ag

Type	Molybdenum (calcic)	Iron (magnesian)	Iron (calcic)	Gold
Metal association (minor metals)	Mo,W (Cu,Bi,Zn)	Fe (Cu,Zn)	Fe (Cu,Co,Au)	Au (Cu,Bi,Te,As,Co)
Tectonic setting	Continental margin Late orogenic	Syn-orogenic	Oceanic island arc; rifted continental margins	Oceanic island arc; rifted back-arc basin margins
Associated intrusive rocks	Quartz monzonite to granite	Granodiorite to granite	Gabbro to syenite, mostly diorite	Gabbro to granodiorite mostly diorite- quartz diorite
Intrusive morphology	Stocks	Small stocks, dikes, sills	Large to small stocks, dikes	Stocks, sills and dikes
Intrusive alteration	Quartz veins, K-silicate	Minor endoskarn, propylitic	Extensive endoskarn Na-silicates	Moderate endoskarn K-silicates
Ore mineralogy	Molybdenite, scheelite, bismuthinite pyrite, chalcopyrite	Magnetite, pyrite, chalcopyrite, sphalerite, pyrrhotite	Magnetite, chalcopyrite, cobaltite, pyrrhotite	Native gold, chalcopyrite, pyrrhotite, arsenopyrite, tellurides, bismuthinite, pyrite
Typical size (million tonnes)	0.1–2	5–200	5–150	0.4–10
Typical grade	0.1–2% MoS ₂	40% Fe	40% Fe	2–15 g/t Au (Average worldwide 4.5 g/t Au)

After Einaudi *et al.*, 1981; Einaudi and Burt, 1982; Meinert 1989; Ray *et al.*, 1988, 1990.

TABLE 8-4

Exoskarn Composition and Main Gangue Mineralogy of Calcic Skarn Deposit Subclasses

Type	Iron	Tungsten	Copper	Zinc-lead	Tin-tungsten	Gold
Exoskarn composition	High Fe Low S, Mn	High Al, Fe Low S	High Fe, S Low Al, Mn	High Fe, Mn, S Low Al	High Al, F Low Fe, S	High Fe, S Low Mn
Early minerals	Ferrosalite (Hd20-80), grandite (Ad20-95), epidote, magnetite	Ferrosalite- hedenbergite (Hd60-90, Jo5-20), grandite (Ad10-50), vesuvianite, wollastonite	Andradite (Ad60-100), diopside (Hd5-50), wollastonite	Manganian hedenbergite (Hd30-90, Jo10-40), andraditic garnet (Ad20-100, Spess 2-10), bustamite, rhodonite	Vesuvianite, spess- rich grandite, Sn andrad, malaya, danbur, datolite	Grandite (Ad10-100) Ferrosalite-hedenbergite (Hd10-100), orthoclase, wollastonite, biotite, epidote,
Late minerals	Amphibole, chlorite, ilvaite, epidote.	Spessartine (5-35), almandine (5-40), grandite, biotite, hornblende, plagioclase.	Actinolite, (chlorite, montmorill.)	Mn actin, ilvaite, chlorite, dannemor, rhodochr	Amphibole, mica, chlorite, tourm, fluo	Amphibole, prehnite, chlorite, scapolite,

Abbreviations: actin=actinolite; Ad=andradite; amphi=amphiboles; andrad=andradite; danbur=danburite; dannemor=dannemorite; fluo=fluorite; Hd=hedenbergite; Jo=johannsenite; malaya=malayite; montmorill=montmorillonite; rhodochr=rhodochrosite; spess=spessartine; tourm=tourmaline. After Einaudi et al., 1981; Einaudi and Burt, 1982; Meinert, 1989; Ray et al., 1988, 1990.

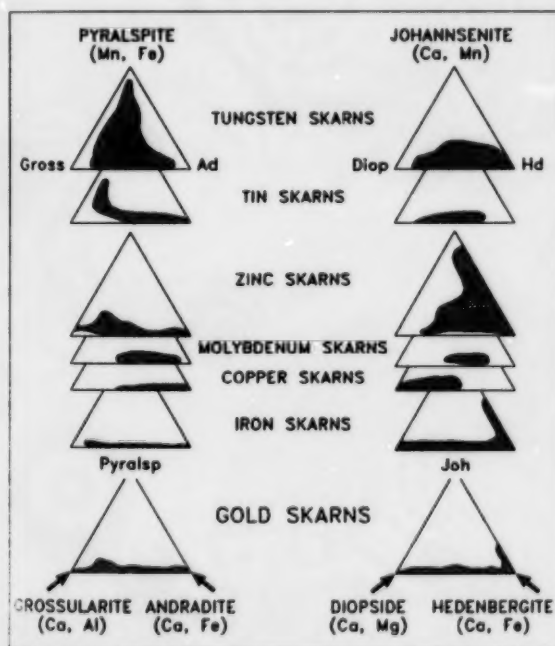


Figure 8-4. Composition of garnets and pyroxenes from W, Sn, Zn-Pb, Mo, Cu, Fe and Au skarns. (Data for Au skarns from Ettlinger and Ray, 1989; other data from Einaudi et al., 1981; Meinert, 1983.)

ratios averaging 1.60. Systematic variations also exist in the $\text{TiO}_2:\text{Fe}_2\text{O}_3$ and $\text{Fe}_2\text{O}_3:\text{FeO}$ ratios of the intrusions (Figure 8-6E and 6F). The latter figure is revealing; it indicates that intrusions related to gold and tin skarns, while differing markedly in their total iron contents, have the most reduced oxidation states. By contrast, intrusions associated with zinc-lead skarns are the most oxidized.

To summarize, systematic correlations exist between the metal chemistry of skarn deposits and the geochemistry of their associated intrusions. These changes suggest a link between the dominant metal in a skarn and magmatic differentiation processes, which are in turn influenced by the magma source and overall tectonic setting (Meinert, 1983). Many of these chemical differences reflect the increasing influences of differentiation, fractionation and continental crust as a source for the plutonic rocks in tin and molybdenum skarns, whereas those related to gold, calcic iron and the island arc hosted copper skarns are derived from more primitive oceanic crust and are the least differentiated of all. While the intrusions related to tin and gold skarns have major differences in chemical composition and depth of emplacement, $\text{Fe}_2\text{O}_3:\text{FeO}$ ratios suggest they both have similar, highly reduced oxidation states (Figure 8-6F).

MORPHOLOGY OF SKARNS

The overall morphology and extent of a skarn depends largely on the size of the hydrothermal system, the permeability of the host rocks and the pres-

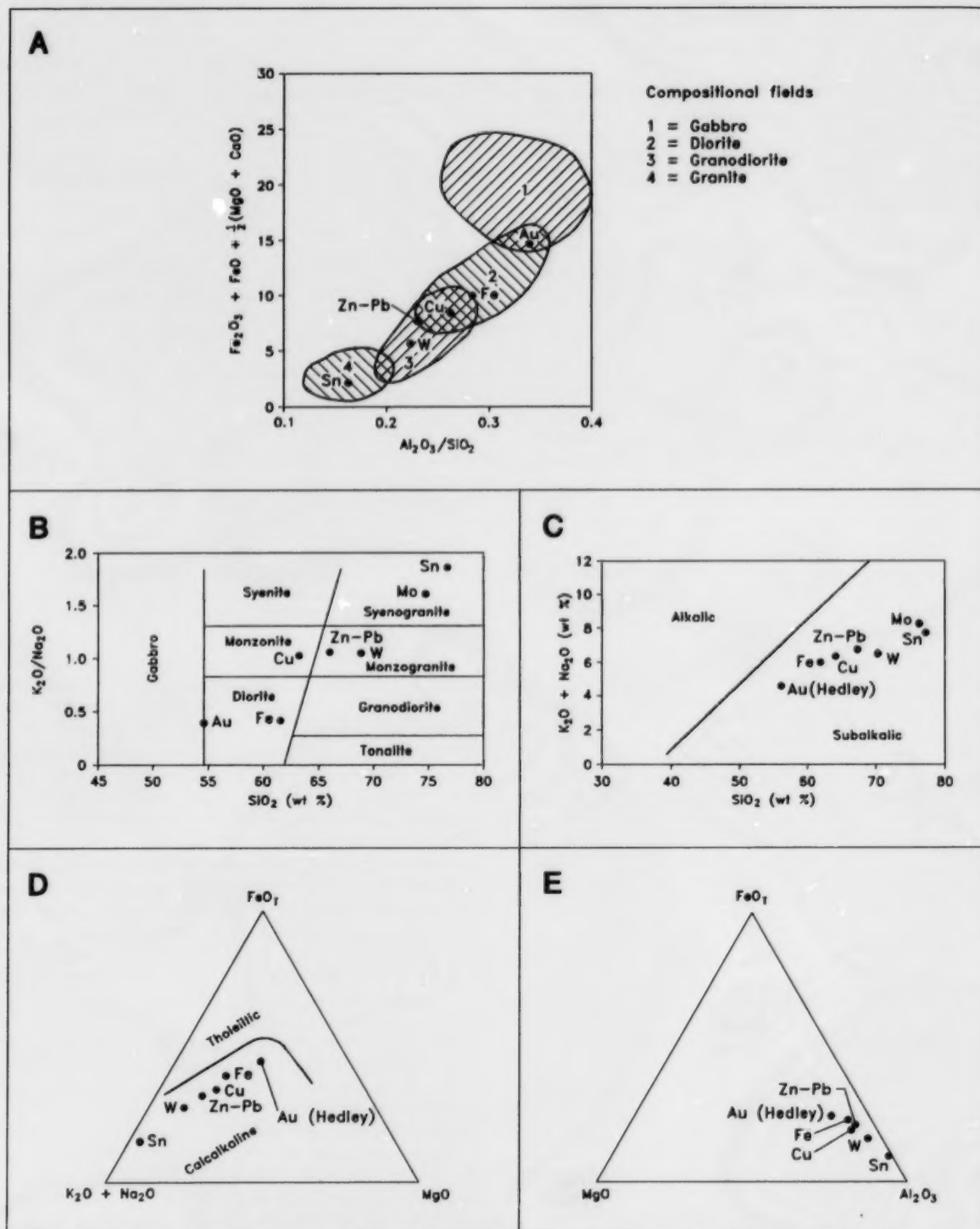


Figure 8-5. Plots, using mean geochemical values, of intrusions associated with various skarn deposit sub-classes. For data see Table 8-5; analytical values for Fe, Cu, Zn-Pb, W, Mo and Sn skarns compiled by Meinert (1983); data for Au skarns (Hedley intrusions) from Ray et al., 1988; Ray and Dawson, in preparation.

A. Principal oxide plot (after Church, 1975) illustrating variable compositions of the skarn-related intrusions.

B. K_2O/Na_2O vs. SiO_2 plot illustrating variable compositions of skarn-related intrusions. Compositional fields modified from Mason (1978).

C. Alkali vs. silica plot illustrating the subalkalic affinities of the skarn-related intrusions.

D. AFM plot illustrating the calcalkaline affinities of the skarn-related intrusions.

E. Iron-magnesium-alumina plot.

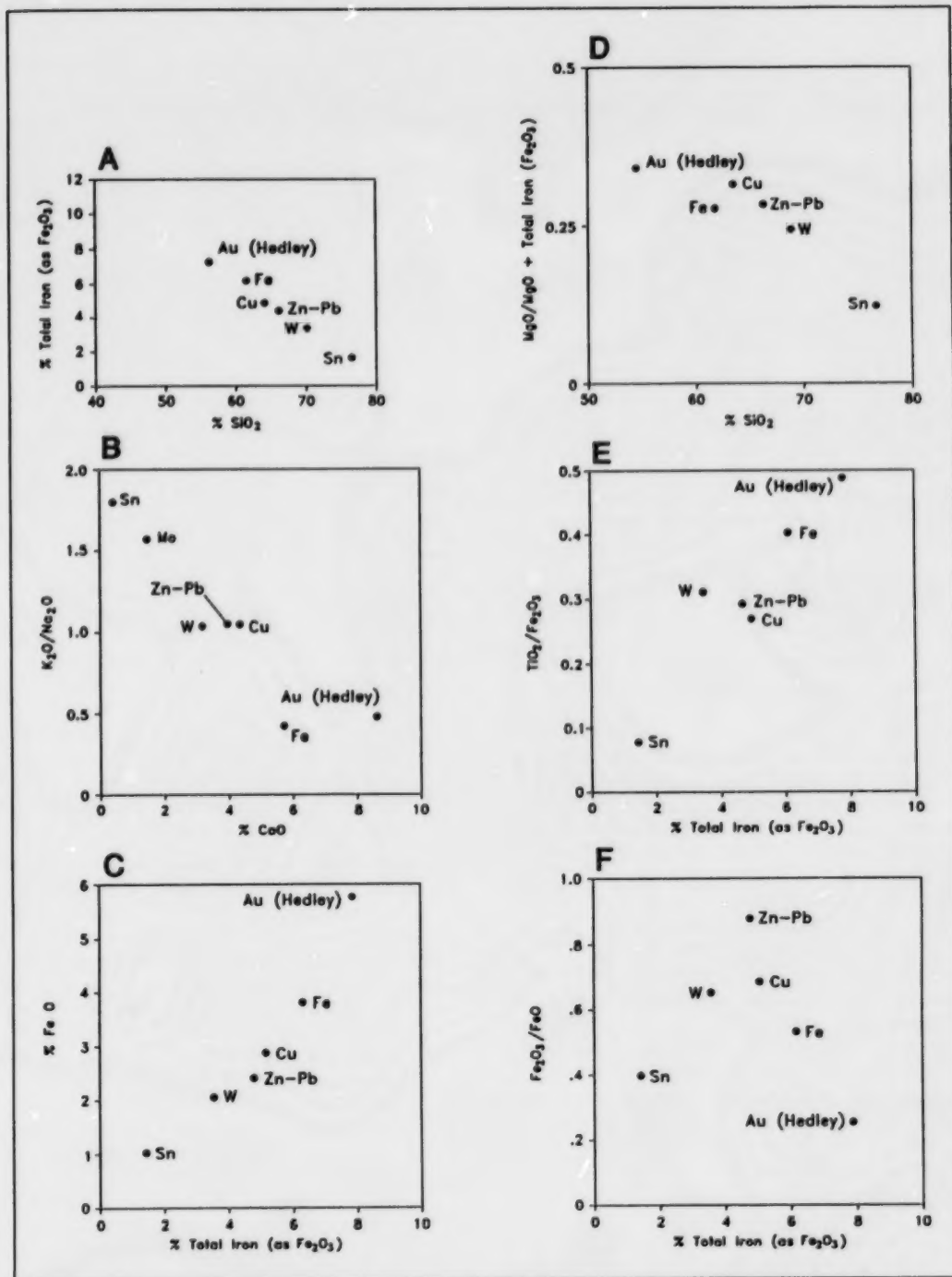


Figure 8-6. Plots, using mean geochemical values, of intrusions associated with various skam deposit subclasses. For data see Table 8-5.

- A. Total iron (expressed as Fe_2O_3) vs. silica plot. NOTE: Intrusions associated with the Hedley gold skams are more iron-rich and silica-poor than those associated with other skam subclasses.
- B. $\text{K}_2\text{O}/\text{Na}_2\text{O}$ vs. calcium plot. NOTE: Intrusions related to tin skams are the most calcium-poor and alkali-rich.
- C. FeO vs. total iron (expressed as Fe_2O_3) plot.
- D. $\text{MgO}/\text{MgO} + \text{total iron}$ vs. SiO_2 plot. NOTE: Intrusions related to the Hedley gold skams are the most ferro-magnesium-rich.
- E. $\text{TiO}_2/\text{Fe}_2\text{O}_3$ vs. total iron (expressed as Fe_2O_3).
- F. $\text{Fe}_2\text{O}_3/\text{FeO}$ vs. total iron (expressed as Fe_2O_3). NOTE: Intrusions related to the Hedley gold skams contain the lowest ferric/ferrous ratios suggesting they have the most reduced oxidation state.

TABLE 8-5

Chemical Compositions of Igneous Rocks Associated with Seven Major Subclasses of Skarn Deposits

	Fe		Cu		Zn-Pb		W		Mo		Sn		Au (Hedley)	
	mean	range	mean	range	mean	range	mean	range	mean	range	mean	range	mean	range
SiO ₂	61.5	(47.2-74.7)	63.5	(55.2-73.7)	66.2	(57.1-76.3)	68.9	(62.6-72.8)	74.8	(73.1-76.0)	76.6	(75.4-78.0)	54.6	(48.3-59.5)
TiO ₂	0.8	(0.2-3.1)	0.5	(0.0-1.0)	0.6	(0.2-1.6)	0.4	(0.1-0.7)	0.2	(0.1-0.3)	0.03	(0.01-0.04)	0.7	(0.5-1.0)
Al ₂ O ₃	17.3	(13.1-22.3)	16.6	(14.3-20.4)	15.4	(12.1-16.3)	15.5	(14.0-16.8)	14.3	(13.0-15.1)	12.6	(10.5-13.8)	18.5	(15.5-20.2)
Fe ₂ O ₃	2.0	(0.5-5.6)	1.9	(0.03-3.2)	2.1	(1.0-3.0)	1.3	(0.2-2.3)	—	—	0.4	(0.0-0.9)	1.4	(0.4-3.1)
FeO.....	3.8	(0.4-11.2)	2.8	(0.7-5.8)	2.4	(0.2-5.0)	2.0	(0.8-3.2)	0.5	(0.0-1.5)	1.0	(0.2-1.4)	5.9	(4.1-7.9)
Fe ₂ O ₃ T*.....	6.2	—	5.0	—	4.7	—	3.5	—	—	—	1.5	—	7.9	(5.8-10.9)
MnO.....	0.1	(0.0-0.3)	0.2	(0.0-1.8)	0.1	(0.0-0.3)	0.1	(0.0-1.0)	0.03	(0.0-0.05)	0.1	(0.0-0.2)	0.14	(0.07-0.19)
MgO.....	2.3	(0.2-4.9)	2.2	(0.7-4.2)	1.8	(0.1-4.2)	1.1	(0.1-2.6)	0.5	(0.3-0.9)	0.2	(0.1-0.4)	4.0	(2.5-8.5)
CaO.....	5.7	(0.7-11.4)	4.3	(1.8-7.6)	4.0	(0.4-6.3)	3.2	(1.9-4.6)	1.2	(0.5-2.0)	0.5	(0.4-0.7)	8.6	(6.5-11.9)
Na ₂ O.....	4.4	(2.9-7.7)	3.3	(1.0-5.3)	3.5	(1.6-4.3)	3.4	(2.7-4.0)	3.1	(1.9-4.2)	2.8	(0.8-3.6)	3.2	(2.0-4.8)
K ₂ O.....	1.7	(0.3-3.4)	3.4	(1.3-5.4)	3.6	(2.0-5.2)	3.5	(2.4-5.4)	5.0	(2.8-7.9)	4.6	(4.2-5.0)	1.4	(0.5-2.5)
P ₂ O ₅	0.27	(0.0-0.4)	0.25	(0.0-0.4)	0.26	(0.0-0.6)	0.15	(0.1-0.3)	0.08	(0.0-0.1)	0.01	(0.0-0.03)	0.18	(0.14-0.26)
Fe ₂ O ₃ /FeO.....	0.53	(0.12-2.36)	0.68	(0.01-1.04)	0.87	(0.49-6.18)	0.65	(0.09-1.23)	—	—	0.40	(0.01-1.35)	0.24	(0.05-0.44)
K ₂ O/Na ₂ O.....	0.39	(0.05-0.85)	1.03	(0.38-1.71)	1.03	(0.53-3.06)	1.03	(0.61-1.87)	1.61	(0.67-4.16)	1.64	(1.17-6.25)	0.44	(0.2-0.66)
Number of samples.....	18		17		9		17		3		9		28	

Data from Meinert (1983), Ray and Dawson (in preparation).

* Total iron expressed as Fe₂O₃.

ence of controlling structures. In British Columbia the following three morphological types of skarn are commonly recognized (Figure 8-7):

- (1) **Pervasive and massive exoskarn envelopes.** These are of variable size but are commonly developed adjacent or peripheral to the genetically related intrusions. They can overprint stratigraphy (Figure 8-7A) and their morphology may be strongly influenced by the morphology of the intrusion; structures tend to have only a local control on the skarn. Examples include the gold skarns of the Hedley camp.
- (2) **Vein-related skarns.** These are characterized by quartz or sulphide veins (commonly gold-bearing) that are enveloped by pervasive, generally barren skarn alteration in the wall rocks (Figure 8-7B). The veins and adjacent skarn are commonly narrow and elongate and exhibit strong fracture control. The genetically related intrusions may or may not be found close to the veins.

An example of this type may be the Nambija deposit in Ecuador, in which gold and minor garnet occur in quartz veins enveloped by skarn (T.G. Theodore, personal communication, 1991). In British Columbia this type is represented by the Second Relief gold deposit, in the Nelson mining camp, which produced 3.1 tonnes of gold (Höy and Andrew, 1989). Several subparallel quartz veins, up to 4 metres in width and several hundred metres in length, cut volcanic and intrusive rocks; carbonates have not been observed. The veins contain minor pyrite, pyrrhotite, chalcopyrite, magnetite and garnet with traces of molybdenite and gold; mineralization is geochemically anomalous in arsenic, antimony and bismuth. Barren skarn alteration overprints both volcanics and diorite adjacent to the veins; it is highly siliceous and contains

coarse andraditic garnet, pyroxene, epidote, amphibole and biotite with trace tourmaline (Ettlinger and Ray, 1989). The veins appear to be genetically related to, but postdate, much of the skarn alteration. Other examples of this type include the gold-copper-bearing sulphide veins in the Rossland mining camp (Wilson *et al.*, 1990; Höy *et al.*, 1992). These deposits are associated with wallrock skarn assemblages that are geochemically anomalous in gold, cobalt, arsenic and nickel.

- (3) **Stratiform skarns.** These are characterized by their concordant nature and thin but extensive morphology (Figure 8-7C). They have a variable sulphide content and the parent intrusion may, or may not, be close to the skarn. Some probably represent reaction skarns formed along the contact between two reactive lithological units. Many others undoubtedly represent infiltration metasomatic skarns formed as a result of long-travelled magmatic fluids moving along favourable, highly permeable horizons. However, the origin of some stratiform skarns is controversial. A few may represent syngenetic metalliferous sediments that were thermally metamorphosed by later intrusions. A syngenetic versus epigenetic origin for the magnetite-rich bedded skarns at San Leone, Sardinia, is discussed by Verkaeren and Bartholome (1979). Other stratiform skarns may have developed at shallower depths and were perhaps related to high level intrusions and fluids of exhalative origin. The Australian stratiform zinc skarns described by Stanton (1987) possibly represent exhalite-related mineralization formed syngenetically in sediments just below the sea floor. It is noteworthy that some recent Red Sea metal-bearing sediments are locally recrystallized to an assemblage containing hematite, magnetite, hedenbergitic pyrox-

ene, actinolite and trace andradite garnet (Zierenberg and Shanks, 1983); recrystallization was probably due to the intrusion of basalts into the wet metalliferous sediments.

Several examples of these controversial stratiform skarns occur in southern British Columbia, and some contain characteristics of either exhalative or volcanogenic massive sulphide mineralization. They include the Steep property in the Kamloops district, and the Sylvester K in the Greenwood skarn camp. The Steep property contains a garnet-epidote-amphibole skarn, up to several hundred metres

thick, that is traceable for over 10 kilometres along strike. The skarn contains pyrrhotite and magnetite with pyrite, chalcopyrite, native bismuth, bismuth tellurides and minor gold (Miller *et al.*, 1988; Ettlinger and Ray, 1989). The Sylvester K comprises a steeply dipping zone of massive, gold-bearing pyrite and lesser pyrrhotite and marcasite up to 6 metres thick and 240 metres long (Church, 1986). Minor garnet-epidote-amphibole alteration is found in the adjacent Triassic sedimentary wallrock.

SKARN DEPOSITS

The size of some individual deposits together with typical sizes and grades of the various skarn deposit subclasses are outlined in Tables 8-1, 8-2 and 8-3 and the location of some skarn deposits, worldwide and in British Columbia, are shown in Figures 8-8 and 8-9 respectively. Overall, skarn deposits do not compare in size or economic importance with volcanogenic massive sulphide (VMS) or sediment-hosted deposits, although historically they have been major sources of iron and copper, and currently represent important reserves and producers of tungsten and gold.

IRON SKARNS

The most important iron skarns, with magnetite as the principal ore mineral, are either calcic skarns within island-arc assemblages or Cordilleran-type magnesian skarns developed within Continental margin sequences (Table 8-3). However, large amounts of byproduct magnetite have also been mined from other skarn-types; magnetite-rich ore occurs in some Malaysian tin skarns (Hosking, 1973), in some calcic zinc-lead skarns (*e.g.*, Titley, 1961), and in several large magnesian porphyry copper skarns such as OK Tedi, Papua New Guinea (Bamford, 1972). In British Columbia, byproduct magnetite ore occurs in some calcic copper skarns including the Craigmont deposit (Morrison, 1980).

Iron skarns range up to 300 million tonnes in size and grade up to 45 per cent iron. Major magnesian iron skarns include the Teya and Sheregesh deposits in the U.S.S.R. (Sokolov and Grigorev, 1977). Important calcic iron skarns in British Columbia include the Tasu deposit on the Queen Charlotte Islands which produced 12.2 million tonnes of ore, the Texada Island deposits that produced over 9 million tonnes of magnetite concentrate, and the 1.6 million tonne Merry Widow deposit on Vancouver Island (Figure 8-9).

Many of the calcic iron skarns on Vancouver and Texada islands have a strong stratigraphic control; they are commonly found where Jurassic gabbroic to granodioritic plutons intrude Upper Triassic limestones of the Quatsino Formation. The stratigraphic top and bottom of the limestone, where it is in contact with volcanic or tuffaceous rocks, are the prime locations for iron skarn mineralization. The Merry

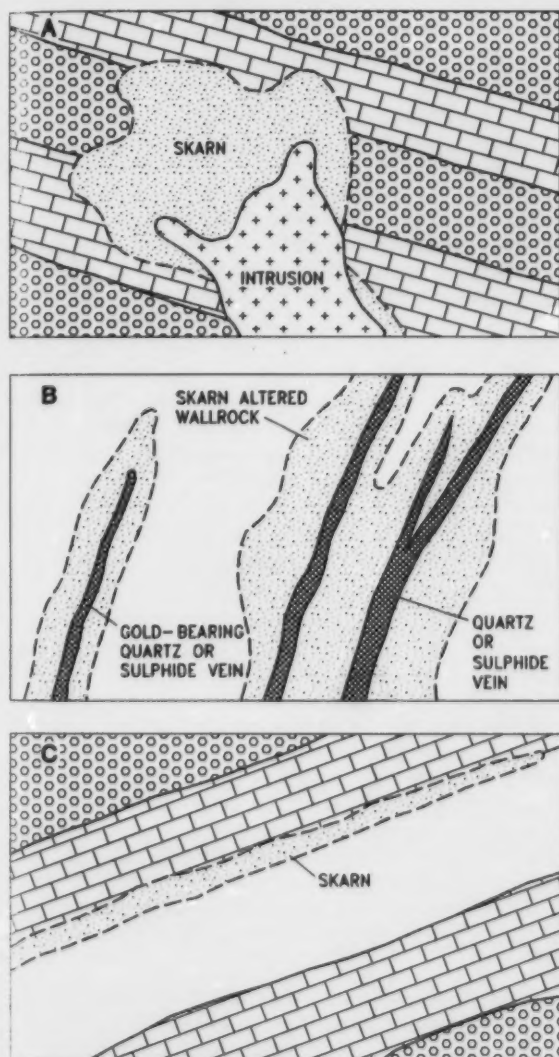


Figure 8-7. Three main morphological types of skarn in British Columbia.

- A. Pervasive and massive skarn; *e.g.*, Nickel Plate deposit.
- B. Vein-related skarn; *e.g.*, Second Relief deposit.
- C. Stratiform skarn; *e.g.*, Steep property and Sylvester K deposit.

TABLE 8-5

Chemical Compositions of Igneous Rocks Associated with Seven Major Subclasses of Skarn Deposits

	Fe		Cu		Zn-Pb		W		Mo		Sn		Au (Hedley)	
	mean	range	mean	range	mean	range	mean	range	mean	range	mean	range	mean	range
SiO ₂	61.5	(47.2-74.7)	63.5	(55.2-73.7)	66.2	(57.1-76.3)	68.9	(62.6-72.8)	74.8	(73.1-76.0)	76.6	(75.4-78.0)	54.6	(48.3-59.5)
TiO ₂	0.8	(0.2-3.1)	0.5	(0.0-1.0)	0.6	(0.2-1.6)	0.4	(0.1-0.7)	0.2	(0.1-0.3)	0.03	(0.01-0.04)	0.7	(0.5-1.0)
Al ₂ O ₃	17.3	(13.1-22.3)	16.6	(14.3-20.4)	15.4	(12.1-16.3)	15.5	(14.0-16.8)	14.3	(13.0-15.1)	12.6	(10.5-13.8)	18.5	(15.5-20.2)
Fe ₂ O ₃	2.0	(0.5-5.6)	1.9	(0.03-3.2)	2.1	(1.0-3.0)	1.3	(0.2-2.3)	—	—	0.4	(0.0-0.9)	1.4	(0.4-3.1)
FeO.....	3.8	(0.4-11.2)	2.8	(0.7-5.8)	2.4	(0.2-5.0)	2.0	(0.8-3.2)	0.5	(0.0-1.5)	1.0	(0.2-1.4)	5.9	(4.1-7.9)
Fe ₂ O ₃ T*.....	6.2	—	5.0	—	4.7	—	3.5	—	—	—	1.5	—	7.9	(5.8-10.9)
MnO.....	0.1	(0.0-0.3)	0.2	(0.0-1.8)	0.1	(0.0-0.3)	0.1	(0.0-1.0)	0.03	(0.0-0.05)	0.1	(0.0-0.2)	0.14	(0.07-0.19)
MgO.....	2.3	(0.2-4.9)	2.2	(0.7-4.2)	1.8	(0.1-4.2)	1.1	(0.1-2.6)	0.5	(0.3-0.9)	0.2	(0.1-0.4)	4.0	(2.5-8.5)
CaO.....	5.7	(0.7-11.4)	4.3	(1.8-7.6)	4.0	(0.4-6.3)	3.2	(1.9-4.6)	1.2	(0.5-2.0)	0.5	(0.4-0.7)	8.6	(6.5-11.9)
Na ₂ O.....	4.4	(2.9-7.7)	3.3	(1.0-5.3)	3.5	(1.6-4.3)	3.4	(2.7-4.0)	3.1	(1.9-4.2)	2.8	(0.8-3.6)	3.2	(2.0-4.8)
K ₂ O.....	1.7	(0.3-3.4)	3.4	(1.3-5.4)	3.6	(2.0-5.2)	3.5	(2.4-5.4)	5.0	(2.8-7.9)	4.6	(4.2-5.0)	1.4	(0.5-2.5)
P ₂ O ₅	0.27	(0.0-0.4)	0.25	(0.0-0.4)	0.26	(0.0-0.6)	0.15	(0.1-0.3)	0.08	(0.0-0.1)	0.01	(0.0-0.03)	0.18	(0.14-0.26)
Fe ₂ O ₃ /FeO.....	0.53	(0.12-2.36)	0.68	(0.01-1.04)	0.87	(0.49-6.18)	0.65	(0.09-1.23)	—	—	0.40	(0.01-1.35)	0.24	(0.05-0.44)
K ₂ O/Na ₂ O.....	0.39	(0.05-0.85)	1.03	(0.38-1.71)	1.03	(0.53-3.06)	1.03	(0.61-1.87)	1.61	(0.67-4.16)	1.64	(1.17-6.25)	0.44	(0.2-0.66)
Number of samples.....	18		17		9		17		3		9		28	

Data from Meinert (1983), Ray and Dawson (in preparation).

* Total iron expressed as Fe₂O₃.

ence of controlling structures. In British Columbia the following three morphological types of skarn are commonly recognized (Figure 8-7):

(1) **Pervasive and massive exoskarn envelopes.**

These are of variable size but are commonly developed adjacent or peripheral to the genetically related intrusions. They can overprint stratigraphy (Figure 8-7A) and their morphology may be strongly influenced by the morphology of the intrusion; structures tend to have only a local control on the skarn. Examples include the gold skarns of the Hedley camp.

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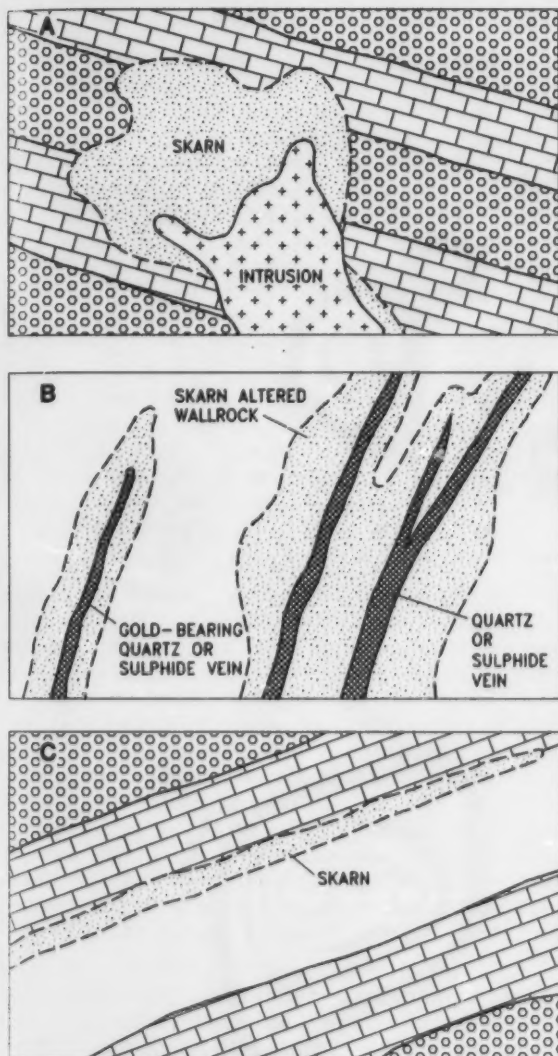


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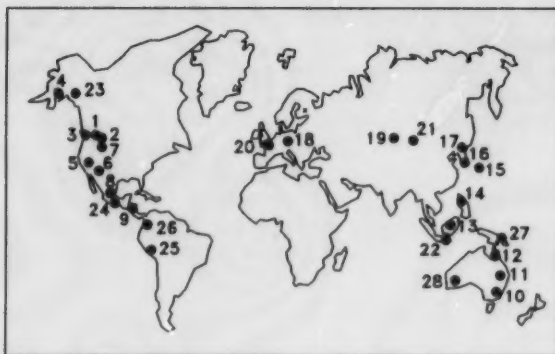


Figure 8-8. World-wide location of some gold and precious metal enriched (PME) skarn deposits, (see Table 8-2 for deposit names).

Widow deposit occurs close to the top of the Quatsino Formation (Ray and Webster, 1991) while the nearby Old Sport copper-gold skarn and the iron skarns of Texada Island are found along the base of the limestone (Webster and Ray, 1990a; 1990b). Some of the iron skarns on Texada Island are both structurally and stratigraphically controlled; magnetite ore at the Prescott mine is concentrated along the subhorizontal base of the Marble Bay Formation limestone (correlative with the Quatsino Formation on Vancouver Island) and along subvertical fault zones in the limestone (Figure 8-10).

Calcic iron skarns are widespread in the Urals, Philippines and coastal British Columbia where they tend to be associated with gabbros and diorites that intrude island-arc volcano-sedimentary sequences (Figure 8-3A). They are commonly associated with extensive exoskarn envelopes that overprint both calcareous sediments and non-carbonate-bearing volcanic rocks (Sangster, 1969; Meinert, 1984). Gangue silicate minerals include grandite garnet and hedenbergitic pyroxene with lesser epidote, actinolite, chlorite, carbonate and quartz. The deposits commonly exhibit widespread calcium metasomatism and may contain albite-scapolite alteration as well as sporadic geochemical enrichment in copper, cobalt, nickel, arsenic and gold. Overall however, copper and gold grades are generally low (<0.2% Cu and 0.5 g/t Au). The Cu:Au ratios of this type of skarn vary from 20 000 to greater than 160 000 and the Cu:Ag ratios range between 2500 and 5000 (Ettlinger and Ray, 1989).

The magnetite is commonly crystalline and in some cases was introduced relatively early since it is locally overgrown and cut by veins of garnet. Much of the crystalline magnetite is believed to form by replacement, but in some deposits there is textural evidence, such as cross cutting veins and dikes of magnetite, to suggest that some magnetite was intruded as a liquid. Next to the Merry Widow deposit (largely comprising coarse crystalline magnetite) the

limestones are cut by two steeply plunging, subcircular magnetite pipes, called the Kingfisher deposits, that reach 50 metres in diameter. Contacts between these deposits and the limestone are extremely sharp, and wallrock skarn alteration around the pipes is minimal. Moreover, most of the magnetite in the pipes has an unusual colliform texture. Stevenson and Jeffrey (1964) argued that this magnetite was deposited as a gel by colloidal processes. However, the morphology of the pipes suggests forcible intrusion and these deposits warrant study to determine whether they are the result of an iron oxide magma similar to that described in the subaerially developed, volcanogenic Cerro de Mercado iron deposit of Mexico (Lyons, 1988).

Pyrrhotite, pyrite and chalcopyrite are generally present in only minor amounts, yet some calcic iron skarns in the Insular Belt of British Columbia, have produced substantial amounts of byproduct gold, silver and copper; the Tasu and Texada Island iron deposits (Figure 8-9), for example, produced 1.3 and 0.8 tonnes of gold respectively. The gold in these deposits is commonly associated with pyrrhotite and pyrite-rich veins and pockets that postdate the magnetite ore. At the Merry Widow deposit, the gold-bearing sulphide veins also contain minor bornite, cobaltite, arsenopyrite, sphalerite and tellurobismuthite (Dixon, 1989; Ray and Webster, 1991). Other opaque minerals reported in calcic iron skarns include trace amounts of molybdenite, galena and hematite. The San Leone iron skarn in Sardinia is unusual in containing minor fluorite and scheelite that are believed to have been introduced during the late hydrothermal stage of the mineralization (Verkaeren and Bartholome, 1979).

Cordilleran magnesian iron skarns are found where hypabyssal felsic plutons, of granodiorite, quartz monzonite or granite composition, intrude dolomitic sequences in continental margin orogenic belts (Table 8-3). The high magnetite content is a function of the dolomitic wallrocks rather than the associated igneous intrusions. Magnetite forms more readily in dolomite as the magnesian calcsilicate gangue minerals do not take up much iron in solid solution at oxidation states present in most skarn-forming environments; consequently, any iron in solution tends to form magnetite whereas the same solution encountering limestone would preferentially form iron-rich pyroxene or garnet (Korzshinski, 1955).

Many magnesian iron skarns are characterized by a gangue assemblage that includes clinopyroxene, olivine, spinel, phlogopite, xanthophyllite, pargasite, tremolite, brucite and serpentine. Some also contain appreciable sulphides (pyrrhotite, sphalerite, bornite and molybdenite) as well as accessory scapolite and borate minerals such as ludwigite, szaibelyite, fluorborite and kotoite (Podlessky *et al.*, 1991). The sulphides and boron minerals generally post date the magnetite mineralization.

COPPER SKARNS

Most of the world's major copper skarns are associated with granodiorite to quartz monzonite stocks, some of which are also related to copper porphyry mineralization, emplaced in continental margin orogenic belts (Table 8-3). By contrast, copper skarns in island-arc environments tend to be associated with quartz diorite to granodiorite plutons. They are less important worldwide, although they are well represented in British Columbia and include the Craigmont and Phoenix deposits (Figure 8-9). Copper skarns are generally characterized by:

- An association with high to intermediate-level felsic porphyritic stocks.
- Proximity to stock contacts.
- High garnet:pyroxene ratios.
- Moderate to high sulphide content.
- Relatively oxidized mineral assemblages (andraditic garnet, diopsidic pyroxene and hematite), although some have more reduced mineral assemblages and a complex metallogeny enriched in W, Mo, Bi, Zn and Au.

Einaudi *et al.*, (1981) note that a continuum may exist between smaller copper skarns associated with

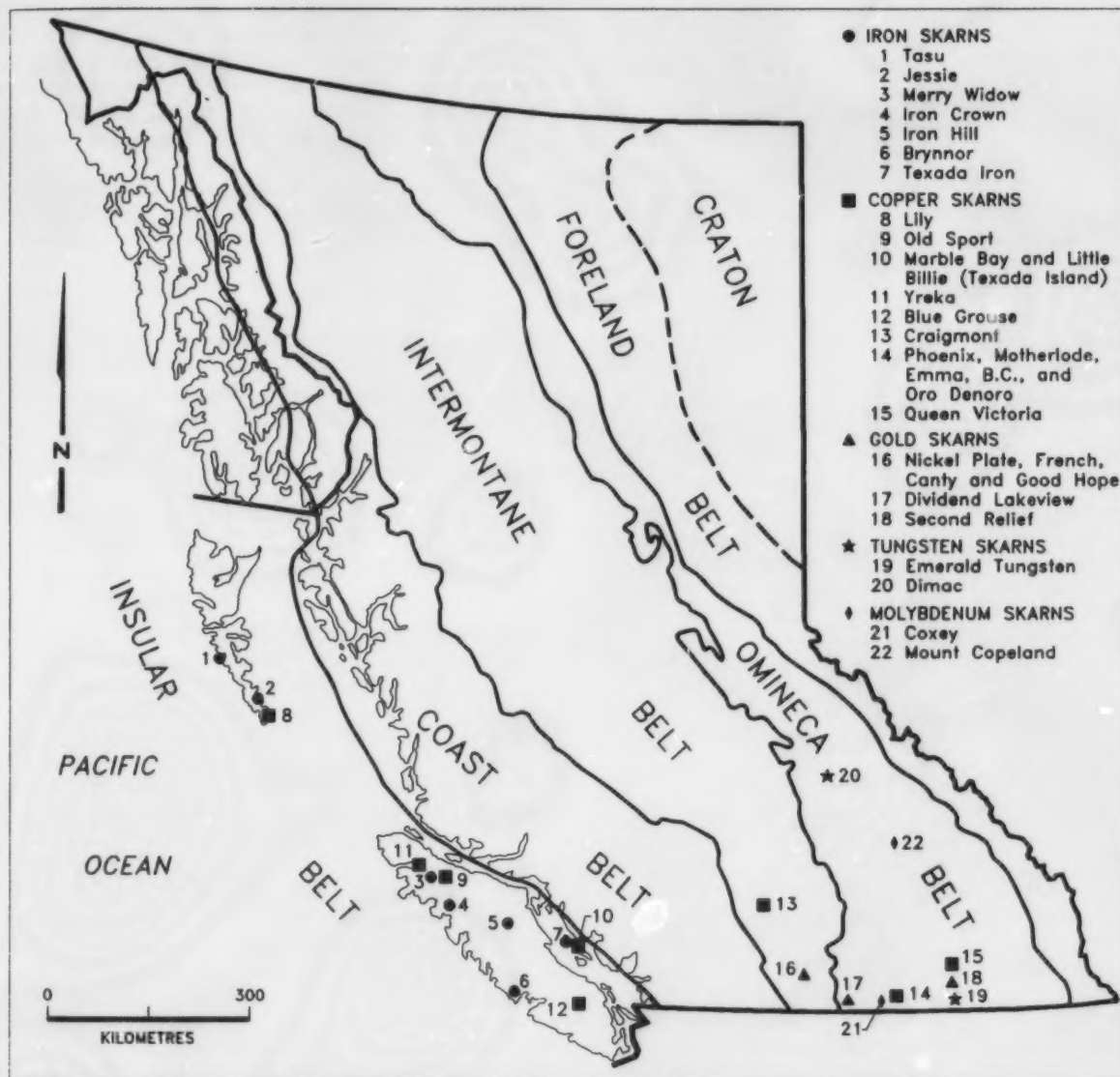


Figure 8-9. Distribution of tectonic belts and some skarn deposits with recorded production in British Columbia; see legend for name of mine.

unaltered, barren stocks and larger copper skarns related to copper porphyry stocks. The latter tend to have higher sulphide contents, more extensive retrograde alteration, and more ferric-rich garnets; they also commonly exhibit a well marked prograde mineral zoning in the exoskarn envelopes.

Copper skarns related to high-level porphyry copper mineralization are well represented in North America. They include those in the Bingham mining district of Utah, U.S.A (Atkinson and Einaudi, 1978), the Mines Gaspé area of Quebec (Allcock, 1982; Shelton 1983), and numerous deposits in Nevada, Arizona and New Mexico (e.g., Perry, 1969; Nielson, 1970; James, 1976; Westra, 1982). They develop mostly in calcic rocks, and the phases of prograde and retrograde alteration are often coevally related to alteration in the plutons. Prograde skarn correlates with potassium-silicate alteration in the pluton while skarn destruction or silica-pyrite replacement of limestone is related to hydrolytic alteration in the pluton.

The variability of these skarns depends largely on the degree of retrogression, marked by sericitic alteration, affecting the porphyry copper deposit. With increasing alteration, the hydrous silicates become progressively depleted in calcium. These skarns are commonly associated with silica-pyrite or silica-hematite alteration that replaces limestone as massive irregular bodies, mantos or structurally controlled breccia pipes.

Exoskarn grades for the porphyry-related copper skarns, such as those at Bingham, Utah and Twin Buttes, Arizona, average from 0.6 to 0.9 per cent copper with deposits ranging between 50 and 500 million tonnes in size. British Columbia's largest copper skarn, the 29.3 million tonne Craigmont deposit, produced over 400 000 tonnes of copper and 140 000 tonnes of magnetite ore. Although it lies within a copper porphyry mining district, Morrison (1980) concluded it is probably not related to a porphyry system.

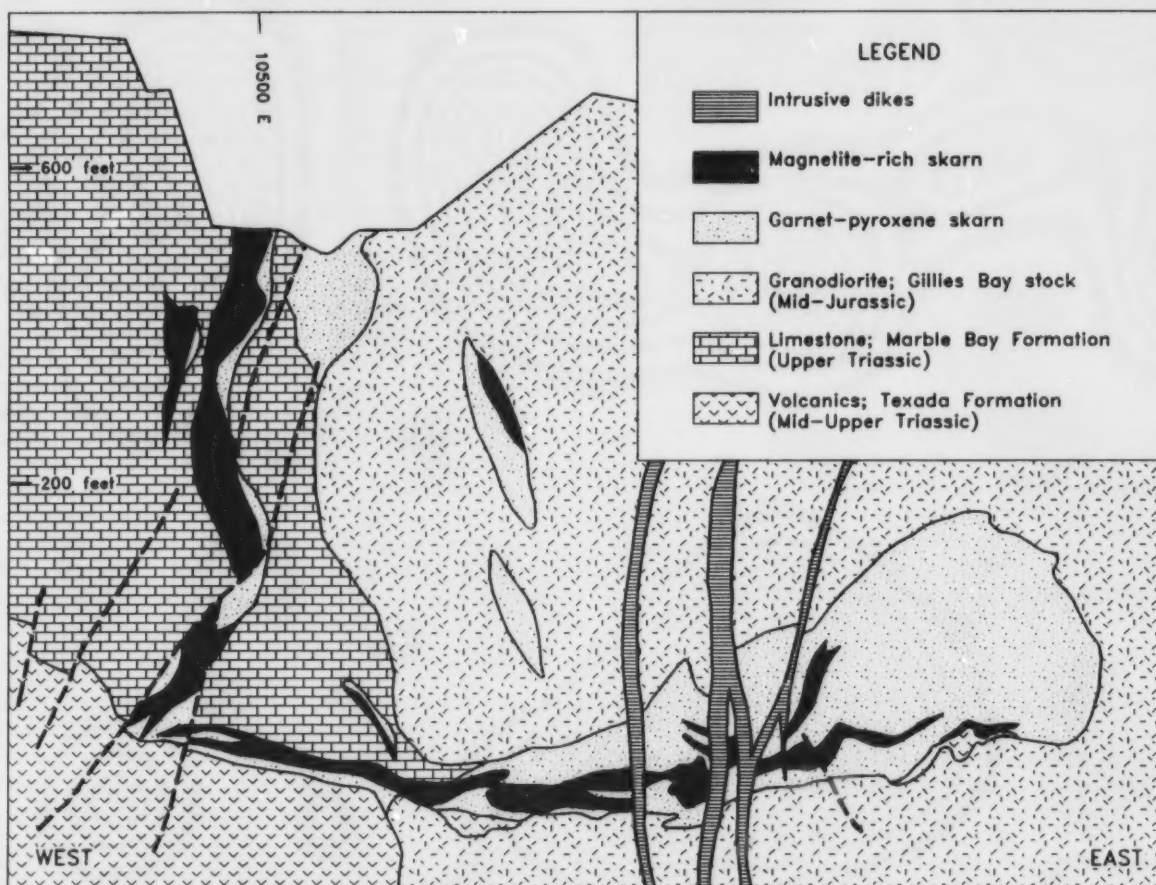


Figure 8-10. East-west geological cross-section through the Prescott Iron skarn, Texada Island. Note the proximal, subhorizontal mineralization is stratigraphically controlled along the limestone-volcanic contact, while the distal, subvertical mineralization is fracture controlled and is associated with narrower skarn alteration zones. From Webster and Ray, (1990a), data courtesy of Ideal Cement Company.

Calcic copper skarns associated with barren stocks tend to be smaller but slightly higher grade than those related to porphyries (Table 8-1). Examples include the 1.5 million tonne Mason Valley deposit in Nevada, which grades 2.5 to 3 per cent copper (Einaudi, 1977), and the 1 million tonne San Pedro deposit in New Mexico which averages between 2 and 3 per cent copper (Atkinson, 1976).

TUNGSTEN SKARNS

The majority of the world's tungsten production comes from various types of deposits in China and the U.S.S.R. However, 58 per cent of the Western World's tungsten production is from skarn (Bender, 1979), mostly from deposits in Australia and North America. The bulk of the world's tungsten production and reserves comes from a few large skarn deposits such as King Island in Tasmania (Edwards *et al.*, 1956; Large, 1971; Tan and Kwak, 1979), Sangdong in Korea (Farrar *et al.*, 1978), Pine Creek in California (Newberry, 1982; 1991), and the Mac-tung and Cantung deposits in Canada (Archibald *et al.*, 1978; Dick and Hodgson, 1982). The Mac-tung, with estimated reserves of over 30 million tonnes, grades 0.95 per cent WO_3 (Dick, 1976). The Salau deposit in southern France contains 930 000 tonnes of ore grading 1.5 per cent WO_3 (Fonteilles *et al.*, 1989). As well as scheelite, it contains pyrrhotite, arsenopyrite and some gold.

Tungsten skarns are commonly formed where deeper level, coarse-grained granodiorite to quartz monzonite intrudes eugeosynclinal limestone-shale sequences. Their geology and mineralogy differ markedly from copper and zinc-lead skarns in that they form at comparatively higher temperatures and deeper crustal levels. They tend to suffer extensive retrogression which is commonly associated with higher ore grades.

Newberry (1979) separates tungsten skarns into two types: reduced tungsten skarns formed in carbonaceous rocks or at greater depths, and oxidized types formed in either noncarbonaceous or hematitic rocks, or at shallower depths. Reduced types are characterized by hedenbergitic pyroxene, magnetite, iron-rich biotite, trace native bismuth and high pyrrhotite:pyrite ratios; locally they may also contain scapolite, vesuvianite and fluorite (Lowell, 1991). The oxidized types have low pyrrhotite:pyrite ratios and their diagnostic minerals are salitic pyroxene, epidote and andraditic garnet.

Tungsten skarns are relatively small and unimportant in British Columbia although over 80 per cent of the province's historic tungsten production (approximately 7500 tonnes of concentrate out of a total of 9194 tonnes) is from skarn. Most of this was derived from several deposits in one small part of the Salmo mining district of southeastern British Columbia (Fyles and Hewlett, 1959). These deposits were worked at the Emerald Tungsten, Dodger, Invincible

and Feeney mines; the Emerald Tungsten (Figure 8-9) and Feeney deposits lie on the margins of a Cretaceous stock where it intrudes Lower Cambrian calcareous sediments. Mineralization consists of scheelite with pyrrhotite and minor wolframite, molybdenite and powellite in a gangue of garnet, pyroxene, actinolite and epidote. Production figures for the individual mines are uncertain but totalled 7416 tonnes of concentrate (Table 8-6) from ore grading 0.5 to 1.5 per cent WO_3 .

Minor tungsten production is also recorded from another small deposit, the Dimac skarn (Figure 8-9). This deposit is hosted in calcsilicate gneisses close to leucogranite intrusions. It is characterized by a very low sulphide content, and by extremely coarse crystals of garnet (Plate 8-3), scheelite and vesuvianite.

Studies on some small tungsten skarn occurrences in northern British Columbia include those by Cooke and Godwin (1984) and Gower *et al.* (1985).

MOLYBDENUM SKARNS

Compared to porphyry molybdenum deposits, molybdenum skarns are relatively unimportant producers. Their characteristics include:

- An association with more evolved granitic rocks that compositionally resemble the igneous rocks genetically related to porphyry molybdenum deposits.
- Mineralization lies close to intrusive contacts.
- Polymetallic mineralization; besides molybdenum they may contain important quantities of lead, zinc, tungsten, tin and rarely uranium.

Most deposits are calcic skarns with a silicate gangue assemblage that includes garnet, hedenbergitic pyroxene, wollastonite, actinolite and epidote. Besides molybdenite, other opaques may include magnetite, chalcopyrite, pyrrhotite, pyrite, arsenopyrite, sphalerite and rarely bismuthinite. Magnesian molybdenum skarns are rarer; an example is the Cannivan Gulch deposit in Montana which has an olivine-tremolite-serpentine gangue (Schmidt and Worthington, 1977; Einaudi *et al.*, 1981).

Molybdenum skarns reach up to 7 million tonnes in size but are usually smaller. Examples include the Little Boulder Creek deposit in the U.S.A. (Kirkemo *et al.*, 1965; Balla and Smith, 1980) and the Azegour deposit of Morocco (Ridge, 1976). Other major molybdenum skarns include the Mount Tennyson deposit in Australia (Stevens, 1974) which exceeds 1.5 million tonnes of ore and grades 0.19 per cent MoS_2 , and the 7 million tonne Yangchiachangtze deposit in China (Hsieh, 1950) which grades 0.5 per cent MoS_2 (Einaudi *et al.*, 1981).

Molybdenum skarns are small and relatively unimportant in British Columbia; they have accounted for just under 3000 tonnes of concentrate (Table 8-7), derived from the Coxe and Mount Copeland deposits (Figure 8-9).

TABLE 8-6

Skarn Deposit Production in British Columbia by Tectonic Belt

INSULAR BELT: 277 OCCURRENCES, 47 PRODUCERS ^(a)									
	Au (kg)	Ag (kg)	Fe (t)**	Cu (t)	Pb (t)	Zn (t)	Sn (t)	W (t)	Mo (t)
Blue Grouse.....	0.2	2 509	0	6 815	0	0	0	0	0
Indian Chief.....	22.5	1 707	0	1 102	0	0	0	0	0
Brynnor.....	0	0	3 061 117	0	0	0	0	0	0
Iron Hill.....	0	0	2 031 327	0	0	0	0	0	0
Little Billie.....	363	1 198	0	819	0	0	0	0	0
Texada Iron.....	890	23 681	9 289 746	25 480	0	0	0	0	0
Cornell.....	471	2 195	0	1 369	0	0	0	0	0
Marble Bay.....	1 544	12 621	0	6 789	0	0	0	0	0
Iron Mike.....	0	0	82 863	0	0	0	0	0	0
Ford.....	0	0	1 184	0	0	0	0	0	0
Iron Crown.....	0	0	1 275 185	0	0	0	0	0	0
Old Sport.....	3 869	11 731	488 726	41 193	0	0	0	0	0
Merry Widow.....	0	0	1 683 507	0	0	0	0	0	0
Yreka.....	50	4 537	0	3 936	0	0	0	0	0
Benson Lake.....	63	488	0	1 237	0	0	0	0	0
Jessie.....	0	0	2 025 950	0	0	0	0	0	0
Lily.....	51	863	0	574	0	0	0	0	0
Tasu.....	1 340	50 394	12 253 880	59 866	0	0	0	0	0
Maid of Erin.....	0.3	1 487	0	243	0	0	0	0	0
Others (28 skarns)....	155	514	23	650	0.02	5	0	0	0
Totals.....	8 819	113 925	32 193 508	150 073	0.02	5	0	0	0
COAST BELT: 83 OCCURRENCES, 7 PRODUCERS									
	Au (kg)	Ag (kg)	Fe (t)	Cu (t)	Pb (t)	Zn (t)	Sn (t)	W (t)	Mo (t)
Cambrian Chieftan.....	0.5	125	0	74	0	0	0	0	0
Others (6 skarns).....	0.1	24	1	9	0	5	0	0	0
Totals.....	0.6	149	1	83	0	5	0	0	0
INTERMONTANE BELT: 135 OCCURRENCES, 13 PRODUCERS ^(b)									
	Au (kg)	Ag (kg)	Fe (t)**	Cu (t)	Pb (t)	Zn (t)	Sn (t)	W (t)	Mo (t)
Mascot Fraction.....	6 937	1 707	0	871	0	0	0	0	0
French.....	1 362	181	0	21	0	0	0	0	0
Good Hope.....	178	120	0	0.6	0	0	0	0	0
Nickel Plate ^(c)	43 218	4 993	0	981	0	0.004	0	0	0
Craigmont.....	78	243	141 635	402 704	0	0	0	0	0
Others (8 skarns).....	17	264	0	2	7	5	0	0	0
Totals.....	51 790	7 508	141 635	404 580	7	5	0	0	0
OMINECA BELT: 131 OCCURRENCES, 49 PRODUCERS ^(d)									
	Au (kg)	Ag (kg)	Fe (t)	Cu (t)	Pb (t)	Zn (t)	Sn (t)	W (t)**	Mo (t)**
Heino-Money.....	107	104	0	0	0	0	0	0	0
Dividend.....	504	88	0	73	0.07	0.07	0	0	0
— Lakeview.....	16	349	0	597	0	0	0	0	0
Greyhound.....	30 422	194 906	0	250 456	0.6	.008	0	0	0
Phoenix.....	5 406	21 755	0	35 512	0	0	0	0	0
Mother Lode.....	31	6 665	0	4 094	0	0	0	0	0
B.C.(L.882).....	212	2 434	0	2 350	0	0	0	0	0
Emma.....	117	954	0	1 691	0	0	0	0	0
Oro Denoro.....	31	8 464	0	0	0	0	0	0	0
Hunter (Jackpot).....	8	950	0	673	0	0	0	0	0
Queen Victoria.....	0	0	0	0	0	0	0	0	0
Coxey.....	436	12	0	0	0	0	0	0	1 749
Jumbo.....	69	0	0	0	0	0	0	0	0
Kootenay.....	3 118	866	0	20	1	0.1	0	0	0
Second Relief.....	0	0	0	0	0	0	0	0	1 191
Mount Copeland.....	0	0	0	0	0	0	0	7416	0
Emerald Tungsten.....	0	71	0	0	24	71	0	0	0
Piedmont.....	0	0	0	0	0	0	0	105	0
Dimac.....	28	406	0	37	13	2	0	0	0
Others (31 skarns)....	40 505	238 024	0	295 503	35	74	0	7521	2951
Totals.....									
FORELAND BELT: 2 OCCURRENCES, 0 PRODUCERS									
GRAND TOTAL METAL PRODUCTION FROM SKARN IN ALL BELTS									
	Au (kg)	Ag (kg)	Fe (t)	Cu (t)	Pb (t)	Zn (t)	Sn (t)	W (t)	Mo (t)
GRAND TOTALS.....	101 115	359 606	32 335 144	850 239	42	89	0	7521	2951

* (a) production data unknown for 8 deposits.

(b) production data unknown for 3 deposits.

(c) production 1904-1987.

(d) production data unknown for 13 deposits.

** Tungsten, iron and molybdenum reported as concentrate.

At the Coxey, near Rossland in southern British Columbia, equigranular and porphyritic quartz diorite sills and dikes intrude Permian-Carboniferous sediments to produce pyroxene-epidote-biotite skarn with minor garnet. Mineralization is dominated by coarse molybdenite, sporadic scheelite and minor pyrite. The geochemistry of the ore is highly variable; most of the mineralization is barren of gold, but locally it is enriched in gold, tungsten, cobalt, nickel, arsenic, antimony and bismuth.

ZINC-LEAD SKARNS

Zinc-lead skarns have the following features:

- An association with granodiorite to leucogranite that ranges from deep-level batholiths up to sub-volcanic aphanitic dikes and breccia pipes.
- Deposits formed near the margins of deeper level batholiths are smaller and manganese-poor compared to deposits developed at higher crustal levels or further from the intrusions.

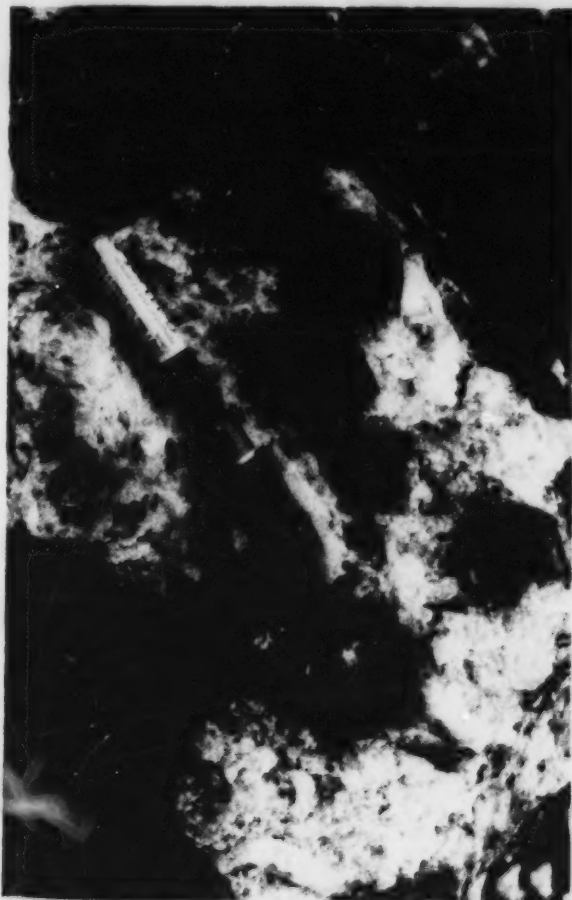


Plate 8-3. Coarse, euhedral garnet crystals with quartz. Dimaç (Silent Lake mine) tungsten skarn, B.C.

- They tend to occur along structural or lithological contacts and may form at considerable distances from the source intrusions.
- They are sulphide rich and pyroxene dominant.

Many calcic zinc-lead skarns are characterized by manganese-rich pyroxenes, as well as assemblages that may include garnet, wollastonite, rhodonite and bustamite. Amphibole, epidote, fluorite, ilvaite, chlorite, rhodochrosite and axinite are commonly reported as retrograde minerals. Besides sphalerite and galena, other opaques may include pyrite and pyrrhotite, with lesser amounts of chalcopryrite, arsenopyrite, hematite, magnetite and molybdenite. Some deposits, such as the Naica in Mexico, contain minor gold (Table 8-2), while others, such as the Ban Ban in Queensland, Australia, include trace bismuthinite (Ashley, 1980). The San Antonio deposit in Chihuahua, Mexico, is unusual in containing trace cassiterite (Allen and Fahey, 1957; Einaudi *et al.*, 1981).

Zinc-lead skarns tend to be small (generally less than 3 million tonnes) but can grade up to 15 per cent zinc and 10 per cent lead; some have a substantial silver content and some gold. These deposits can be associated, either on a local or district scale, with sulphide-rich mantos; many of the limestone hosted Zn-Pb-Ag rich manto-type replacement deposits in Mexico have an early and strong skarn component (Megaw *et al.*, 1988). Larger examples of zinc-lead skarns include the 10 million tonne Naica deposit in Mexico (Erwood *et al.*, 1979; Megaw *et al.*, 1988), which grades 10 per cent zinc, 13 per cent lead, 180 grams per tonne silver and 0.4 gram per tonne gold, and the 3 million tonne Groundhog deposit of New Mexico, grading 12 per cent zinc, 4 per cent lead, 1 per cent copper and 60 grams per tonne silver (Einaudi *et al.*, 1981). The Yeonhwa-Ulchin district of South Korea contains three major skarn deposits that produced 13.5 million tonnes of ore; these accounted for over 80 per cent of the country's zinc and lead production (Yun and Einaudi, 1982).

British Columbia has had only miniscule production from its small and rare zinc-lead skarns (Table 8-7). The largest, the Piedmont, is located southwest of Kaslo in southeastern British Columbia. Massive and disseminated sphalerite-galena-pyrrhotite mineralization in a garnet-pyroxene-epidote gangue is localized in hornfelsed siltstone and limestone (Webster *et al.*, 1992). These metasedimentary rocks occupy a roof pendant within the granodioritic Nelson batholith.

TIN SKARNS

Tin skarns, which occur as both calcic and magnesian skarn deposits, are characterized by:

- An association with differentiated, ilmenite-series granitic stocks and batholiths (of both I and S-type) that often exhibit greisenization.
- Reduced mineral assemblages.

- Cassiterite with sporadic sphalerite, arsenopyrite and stannite.
- Skarns and associated intrusions may be enriched in Rb, Li, Be, W, Mo, F and B (e.g., Burt, 1978).
- Late assemblages may include fluorite, tourmaline, phlogopite and chlorite.

Tin-bearing minerals include cassiterite and malayaite (CaSnSiO_5), although some tin also occurs in the andraditic garnet, amphibole and epidote. Other minerals present can include arsenopyrite, pyrrhotite, sphalerite, bismuthinite, magnetite, chalcopyrite and scheelite.

Tin skarn deposits may reach 30 million tonnes in size but are usually smaller and of minor economic importance due to low grades. They may grade up to 1.0 per cent tin, but some of the metal in these deposits is not economically recoverable as it occurs as an essential element in malayaite and as a nonessential component in garnet. Retrogression is often important in producing economic grades in tin skarns. Major examples of tin skarns include the 30 million tonne Moina deposit in Tasmania (Kwak and Askins, 1981) and the 3 million tonne Lost River deposit in Alaska (Kwak, 1987; Dobson, 1982); these grade 0.15 and 0.27 per cent tin respectively. The JC tin deposit, situated in the southern Yukon close to the British Columbia border, has estimated reserves of 1.25 million tonnes grading 0.54 per cent Sn (Layne and Spooner, 1991).

A rare characteristic of some tin skarns, rich in iron, fluorine and beryllium, is to exhibit rhythmic layering or ribbon banded textures (Plate 8-4; Jahns, 1944). Such rocks have been termed "wrigglite" skarns (Askins, 1976; Kwak and Askins, 1981) and their origin has been discussed by Kwak (1987). Unlike most tin skarns, which generally develop at deep levels, wrigglites are believed to form in relatively near-surface conditions such as over the cupolas of high level granites.

British Columbia has had no tin production from skarn, and less than 20 skarn occurrences in the

province report tin mineralization. Most of these occur in the Cassiar district of northern British Columbia (e.g., Mulligan and Jambor, 1968; Ballantyne and Ellwood, 1988) where they are related to a Cretaceous intrusive belt that extends northwards into the Yukon. This belt is marked by tungsten, tin and molybdenum porphyry and skarn-type mineralization, and some of the tin skarns are boron-enriched (Ballantyne, personal communication, 1991). Fluorine bearing tin-tungsten skarns also occur in the Atlin district (Webster *et al.*, 1992). One of these, the Daybreak occurrence, contains rhythmically layered wrigglite skarn (Plate 8-4).

GOLD SKARNS (INCLUDING PME SKARNS)

Skarn deposits worldwide have produced more than 1000 tonnes of gold (Meinert, 1988), and the skarns of British Columbia have contributed over 10



Plate 8-4. "Wrigglite" skarn with alternating layers rich in fluorite, magnetite, vesuvianite and grossular garnet. This skarn contains minor cassiterite and gahnite and is geochemically anomalous in beryllium (S.B. Ballantyne, personal communication, 1991). Daybreak tin skarn occurrence, Atlin district, B.C.

TABLE 8-7

Production from Skarn in British Columbia Compared to Total Production from all Sources (excluding placer)

Metal	total production (t)*	skarn production (t)	% skarn production
Iron.....	36 693 780	32 335 144	88.1
Copper.....	6 606 944	850 239	12.8
Gold.....	615	101	16.4
Silver.....	20 103	359	1.7
Lead.....	8 642 291	42	—
Zinc.....	8 269 490	89	—
Molybdenum.....	265 387	2 951	1.1
Tungsten.....	9 194	7 521	82
Tin.....	10 592	0	—

* Total production data from B.C. mineral statistics annual summary tables (all known sources 1858-1987, excluding placer).

per cent of this total (Tables 8-6 and 8-7). However, a substantial proportion of this gold was produced as a byproduct from mining base metal and iron skarns; in British Columbia for example, 47 per cent of the gold was derived as a byproduct from PME-copper and iron skarns.

Until the 1980s, gold skarns were poorly understood and not widely recognized as a distinct class of skarn deposit. Recently however, considerable study has been devoted to gold skarns by Orris *et al.* (1987), Meinert, (1988, 1989), Ettlinger and Ray (1989), Ray *et al.* (1987, 1988; 1990), Myers and Meinert (1989) and Theodore *et al.* (1991) which has increased our knowledge of these deposits. Discoveries of major gold or PME skarn deposits, such as the Fortitude and McCoy in Nevada (Tingley and Smith, 1982; Wotruba *et al.*, 1986; Kuyper, 1987; Brookes *et al.*, 1990), the Buckhorn Mountain in Washington State (Shannon *et al.*, 1990) and the Red Dome (Torrey *et al.*, 1986; Ewers and Sun, 1988) in Australia, as well as the reopening of the Nickel Plate mine (Simpson and Ray, 1986) have also caused these deposits to be recognized as viable exploration targets.

The available data concerning sizes and grades of 42 gold and PME skarn deposits throughout the world (Figure 8-8) are outlined in Table 8-2. Gold skarns range up to 15 million tonnes in size although deposits between 500 000 and 5 million tonnes are more common. Grades for gold skarns worldwide average 4.5 grams per tonne gold (Meinert, 1989) but some deposits exceed 10 grams per tonne gold. Smaller examples include the 400 000 tonne Southern Cross deposit in Montana and the 500 000 tonne Mount Biggendon deposit in Australia. Major gold skarns include the 5.1 million tonne Fortitude deposit, Nevada, (grading 10.4 grams per tonne gold), the 6.7 million tonne Buckhorn Mountain deposit in Washington grading 3.5 grams per tonne gold (Shannon *et al.*, 1990), and the 15 million tonne La Luz deposit in Nicaragua grading 4.1 grams per tonne gold. The Nickel Plate deposit in British Columbia, which contained some 11.8 million tonnes of underground and open pit ore, is Canada's largest gold skarn (Plate 8-5).

DISTRIBUTION OF GOLD AND PME SKARNS

The distribution of some gold and PME-skarn deposits, both worldwide and in British Columbia are shown in Figures 8-8 and 8-9 respectively, and listed in Table 8-2. Although base metal skarns are developed in a wide variety of geological environments, tectonic regimes and hostrock lithologies (Zharikov, 1970; Einaudi *et al.*, 1981; Kwak, 1987), gold skarns throughout the world are more restricted, and are mostly concentrated in the Phanerozoic mobile belts. They are commonly found in the same geological environment as calcic copper and iron skarns, and there is a worldwide spatial and temporal association between porphyry copper

provinces and gold skarns. A temporal relationship is suggested because both the gold skarns and porphyry copper deposits of North and South America are largely Mesozoic or Cenozoic in age (McMillan and Panteleyev, 1988), while the gold skarns of eastern Australia and central U.S.S.R., like their spatially associated porphyry provinces, are predominantly Paleozoic.

The close association between gold skarns and porphyry copper districts is seen in the Canadian Cordillera; many of the alkalic and calcalkalic porphyry systems lie close to the location of the Mesozoic initial 0.704 - 0.705 $^{87}\text{Sr}/^{86}\text{Sr}$ ratio lines, as defined by Armstrong (1988); (W.J. McMillan, personal communication, 1990), which mark the transition between Phanerozoic ensimatic crust to the west and Precambrian sialic crust to the east. Similarly, the British Columbian gold skarns at Hedley, the Dividend-Lakeview mine and the Oka occurrence (Ettlinger and Ray, 1989) all lie close to this transition. Mesozoic and Cenozoic initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios could assist the location of district-wide exploration targets for gold and PME skarns in the North American Cordillera.

Almost all of the gold skarns in the Canadian Cordillera are genetically related to high to intermediate-level, I-type, late oceanic island-arc plutonism. In most gold skarns in British Columbia the plutons intrude essentially coeval arc superacrustals (at Hedley for example, the skarns and intrusions were probably emplaced less than 20 million years after deposition of the sedimentary hostrocks). However, some PME copper and iron skarn deposits, such as those on Texada and Vancouver islands are exceptions; they are associated with Early to Middle Jurassic continental margin intrusions of the Bonanza magmatic arc, and are hosted in Triassic or older, lithologically favourable oceanic rocks that were unrelated to the arc. Magmatism related to plate construction, or plutons associated with plate collision and accretion, or those exposed in the deeply eroded root zones of arcs are less favourable for gold skarn mineralization. For example, the Coast Belt of British Columbia, despite containing some carbonates and numerous intrusions, has comparatively few skarn occurrences (Figure 8-11) and has produced virtually no skarn-derived gold (Figure 8-12; Table 8-6).

Some gold skarns, such as those in the Hedley camp, are developed in impure calcareous clastic sediments that were deposited along the fracture-controlled edge of a back-arc or marginal basin (Figure 8-3C). Such rifted basin margins are particularly favourable for gold skarns because the controlling basement structures preferentially channel the arc-related plutons into suitable carbonate-rich host rocks. Regionally in British Columbia, the favourable arc or back-arc sequences, such as the Late Triassic Nicola, Stuhini and Takla groups and the Early Jurassic Rossland Group (Figure 8-13), include

potassium-rich volcanic shoshonites and some limestone-boulder breccias or olistostromes; the latter reflect the unstable sedimentary environment that prevailed in the basin-margin facies.

CHARACTERISTICS OF GOLD SKARNS

Many gold skarns are characterized by:

- An association with high to intermediate-level, mafic, iron-rich, commonly dioritic and porphyritic calcalkaline intrusions.
- High pyroxene: garnet ratios in the exoskarn.
- The gold-sulphide mineralization is generally hosted in exoskarn distal to the intrusion, close to the outer, pyroxene-rich margins of the skarn envelope.
- The presence of tellurides.
- Relatively reduced environments which accounts for the high pyrrhotite:pyrite ratios and mineral assemblages containing hedenbergitic pyroxene, arsenopyrite and native bismuth.
- Moderate to high sulphide content.
- Geochemical enrichment in Bi, As, Te or Co. Anomalous selenium values in gold skarns are reported by Hammarstrom *et al.* (1989).
- Prograde skarn development can begin with a phase of potassium metasomatism (biotite, orthoclase), similar to that occurring in some porphyry systems.
- Sporadic presence of chlorine-rich amphibole and late scapolite, which suggests chloride complexes were important for the transport and precipitation of gold in skarns.

Gold at byproduct grades is fairly common in copper skarns and to a lesser extent in iron, tungsten and zinc-lead skarns, but is extremely rare in molybdenum and tin skarns. Gold enrichment is mainly found in calcic skarns; gold and PME magnesian skarns are very rare. However, a significant and recently described exception are the greenstone-hosted magnesian gold skarns in the Yilgarn Block of Western Australia (Mueller, 1988, 1990, 1991). They include the 3.28 million tonne Marvel Loch deposit which produced 9.7 tonnes of gold (Table 8-2); mineralization includes pyrrhotite, lollingite, arsenopyrite, magnetite, ilmenite and scheelite in a gangue of calcite, olivine, pyroxene and amphibole. As well as in their gangue mineralogy, these magnesian gold skarns differ from the better-known Phanerozoic calcic gold skarns in their Archean age.

The overall silicate mineral assemblages associated with the calcic gold skarns are similar to those in calcic iron skarns and some copper skarns, and thus cannot necessarily be used to distinguish skarns with precious metal potential. Both gold and iron skarns commonly contain iron-rich, hedenbergitic pyroxenes whereas the pyroxenes in copper skarns tend to be more iron-poor.

The intrusive rocks associated with gold skarns range compositionally from granite to gabbro although iron-rich quartz diorite and diorite are the most common. The intrusions vary from large stocks to narrow sills and dikes which may occur as swarm complexes (Figure 8-14). Many intrusions are porphyritic with phenocrysts of hornblende and/or



Plate 8-5. The Nickel Plate mill and mine site seen looking south, Hedley, B.C.
(Photograph taken in 1987.)

plagioclase (Plate 8-6); the latter exhibit marked oscillatory and reverse compositional zoning that may indicate the intrusions were derived from hybridized magmas or volatile-rich melts. The low to intermediate initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of these rocks suggest they were derived either from upper mantle material, or more likely represent recycled oceanic crust. Although no gold skarns associated with alkalic rocks have yet been positively identified, some high-level alkalic intrusions related to gold-bearing porphyry copper deposits in British Columbia, such as Copper Mountain, are associated with skarn-like garnet-pyroxene-epidote-scapolite alteration assemblages (Preto, 1972; Hodgson *et al.*, 1976). Since all the recognized skarn subclasses are related to subalkalic, calcalkaline intrusions (Figure 8-5C and 5D) the unique alkalic association of this gold-bearing skarn-like alteration warrants further research.

Many gold and PME skarns exhibit variable mineralogical zoning patterns similar to those described in iron and base metal skarns. At the Nickel Plate deposit for example, a concentric pattern of exoskarn alteration is developed around the associated Toronto stock intrusion with proximal, coarser grained garnet-rich skarn and more distal pyroxene-rich skarn (Figure 8-15). A longitudinal section through the envelope also reveals a subhorizontal zoning. This is manifest as an upper siliceous, fine grained and barren pyroxene-rich zone, a middle zone of generally barren coarser grained pyroxene-garnet-carbonate skarn, and a lower zone of predominantly pyroxene skarn that locally carries abundant scapolite, carbonate, sulphides and gold (Ray and Dawson, in preparation). This basal skarn passes sharply downwards through siliceous marble into unaltered limestone. At the nearby Good Hope gold skarn the mineral zoning is a little different. Passage from endoskarn out to unaltered sediments is marked by the following zones: (1) diopside-rich skarn, (2) garnet-rich skarn, (3) very coarse crystalline hedenbergitic skarn with gold and sulphides, (4) marble, (5) unaltered limestone.

The mineral paragenesis of gold skarns shows overall similarities to other skarn types, although important differences are noted. The Hedley deposits (Ray *et al.*, 1988; Ettlinger *et al.*, in press) and the Fortitude gold skarn (Myers and Meinert, 1989) include an early phase of biotite and potassium feldspar alteration that predates the garnet-pyroxene assemblages. Also at Hedley, the gold mineralization was coeval with widespread scapolitization, both of which were deposited close to the outer margins of the skarn envelope. The overall temporal sequence of mineral deposition in the Hedley skarns was as follows:

1. Biotite, orthoclase and epidote.
2. Clinopyroxene and minor orthoclase and wollastonite.
3. Garnet and clinopyroxene, with minor scapolite and albitic plagioclase.

4. Sulphides (with gold and tellurides) and abundant scapolite, with minor chlorite, epidote, orthoclase, sericite, axinite and vesuvianite.
5. Epidote, chlorite, sericite and prehnite.

Quartz and carbonate crystallized throughout the sequence.

The degree of retrograde alteration (chlorite, epidote, tremolite-actinolite) overprinting the silicate assemblages varies enormously in gold and PME skarns, and cannot be used to indicate gold potential. Gold skarns, like iron skarns, are characterized by low-manganese (<1 weight per cent MnO_2) granitic garnets and low-manganese (<4 weight per cent MnO_2), iron-rich hedenbergitic pyroxenes (Figure 8-4). Data are sparse, but no consistent core-to-rim compositional zoning in garnets in gold skarns has been recognized; the Nickel Plate garnets exhibit variable zoning although grossular cores and andraditic rims are most common (Figure 8-2), while at the Fortitude gold skarns the reverse is seen (Myers and Meinert, 1989).

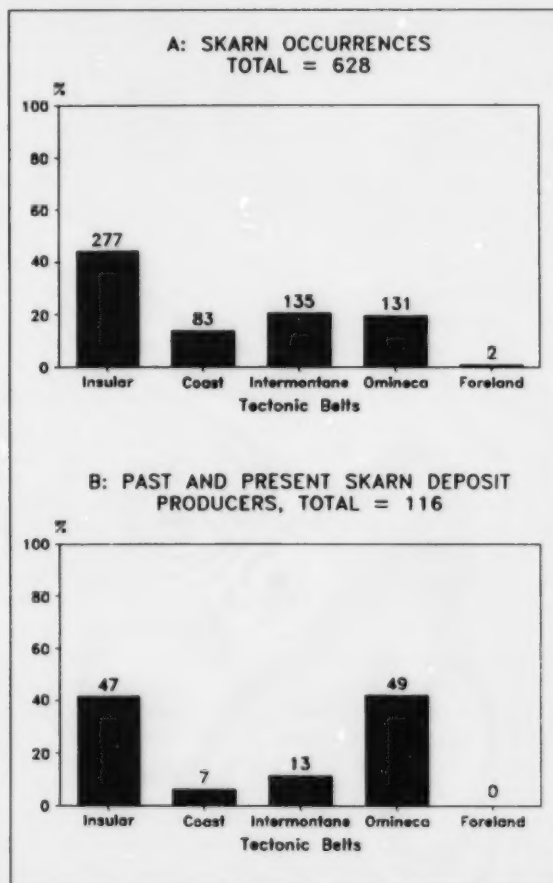


Figure 8-11. Percentages of skarn occurrences (A) and producing deposits (B) in each tectonic belt of British Columbia. (NOTE: Numbers above each box = number of occurrences and producers in each belt.)

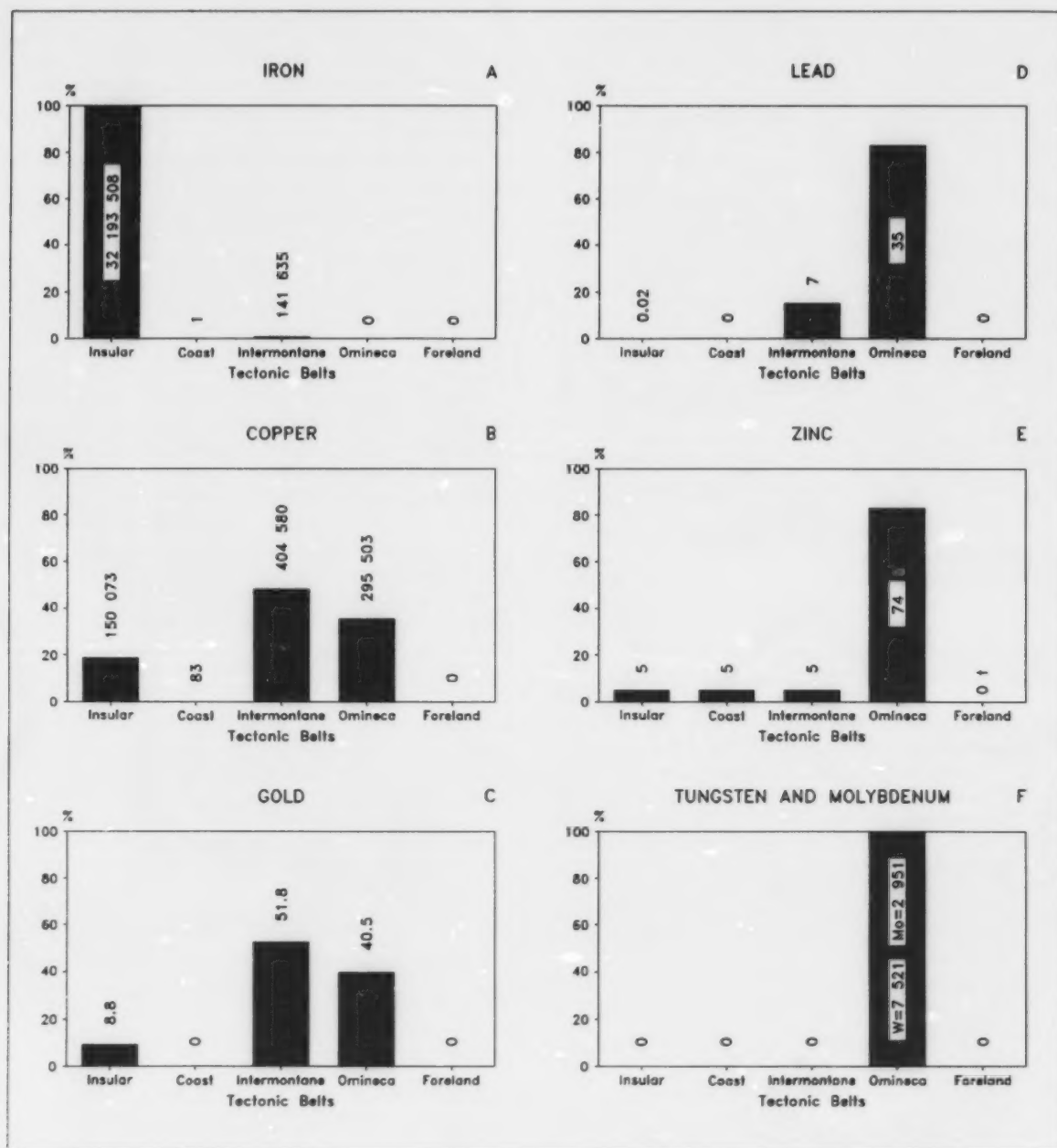


Figure 8-12. Comparative production of iron (A), copper (B), gold (C), lead (D), zinc (E), and tungsten and molybdenum (F) from skarn in British Columbia in relation to each tectonic belt. Numbers within each diagram identify respective metal (Cu, Au, Pb and Zn) or concentrate (Fe, W, Mo) production in tonnes.

Gold mineralization in skarn is associated with opaque minerals that were mainly introduced after the prograde skarn silicate assemblages (Plate 8-7). Pyrrhotite, arsenopyrite, chalcopyrite, pyrite, bornite, sphalerite, magnetite, and bismuth and/or tellurium minerals are the most common opaques in gold and PME skarns. Less commonly, cobaltite, scheelite, molybdenite and galena are also present. Gold generally occurs as microscopic inclusions in the sulphides, and in some deposits it is difficult to visually distinguish ore from waste. There is also a highly variable trace element association; gold and PME skarns may be enriched in As, Te, Bi, Se, Ag, Cu, Co, Zn, Sb, W, Pb, Ni, Mo, or very rarely, Pt. However, in deposits such as the Nickel Plate,

arsenic does not always correlate well with gold (Ray *et al.*, 1988). This is because at least two generations of arsenopyrite are present, an early barren phase that is widely developed, and a later, more restricted phase that is associated with gold, tellurides and cobaltite.

Some gold skarn deposits exhibit systematic geochemical variations throughout the envelope; at the Fortitude and Nickel Plate mines, for example, the copper grades in the skarn increase toward the endoskarn stock. The presence of lead, silver, nickel or, most commonly, bismuth tellurides, is a distinctive characteristic of gold enrichment in skarn, as is the common presence of native bismuth and other bismuth minerals; the tellurides recorded include hedleyite, tetradymite, altaite and hessite. Other minerals reported in gold and PME skarns include bismuthinite, wittichninite, breithauptite, lollingite and maldonite.

Sparse fluid-inclusion data on gold and PME skarns such as Red Dome and Fortitude (Ewers and Sun, 1988; Myers and Meinert, 1989) suggest prevailing temperatures of between 260 to 450°C and fluids with salinities of 2 to 26 weight per cent NaCl equivalent. Higher temperatures for the Nickel Plate gold skarn are suggested; homogenization temperatures of between 460 and 800°C (not pressure corrected) were obtained on fluid inclusions in garnet (Ettlinger *et al.*, in press). Homogenization temperatures in scapolite associated with gold indicate the later mineralization occurred in the range of 320 to 400°C.

Garnet and pyroxene compositions and the mineral assemblages suggest gold enrichment in skarn can develop at a variety of oxidation states (Figure 8-16). The Texada Island and Red Dome PME skarns formed under intermediate to relatively oxidizing conditions, similar to those determined by Einaudi *et al.*, (1981) and Einaudi (1982) for iron skarns and porphyry copper-related copper skarns. Likewise, mineral assemblages in the McCoy gold deposit, Nevada (Brookes *et al.*, 1990) and the McLymont gold skarn in northwest British Columbia (Ray *et al.*, 1991) indicate they developed in relatively oxidized environments. By contrast, all the gold skarns in the Hedley camp developed in a relatively reduced state (Figure 8-16). This conclusion is supported by a number of factors including the iron-rich composition of early biotite at Nickel Plate (Ettlinger *et al.*, in press), the abundance of pyrrhotite and arsenopyrite, the presence of native bismuth, and the general scarcity of pyrite in the Hedley gold camp.

The highly reduced nature of the Hedley intrusions, compared to plutonic rocks associated with the other skarn subclasses, is indicated by the $\text{Fe}_2\text{O}_3/\text{FeO}$ versus total iron plot in Figure 8-6F. Similar plots for the intrusions and hosting sediments at the Nickel Plate deposit are shown in Figures 8-17A and 17B respectively. These illustrate the progressive changes in the total iron content and oxida-

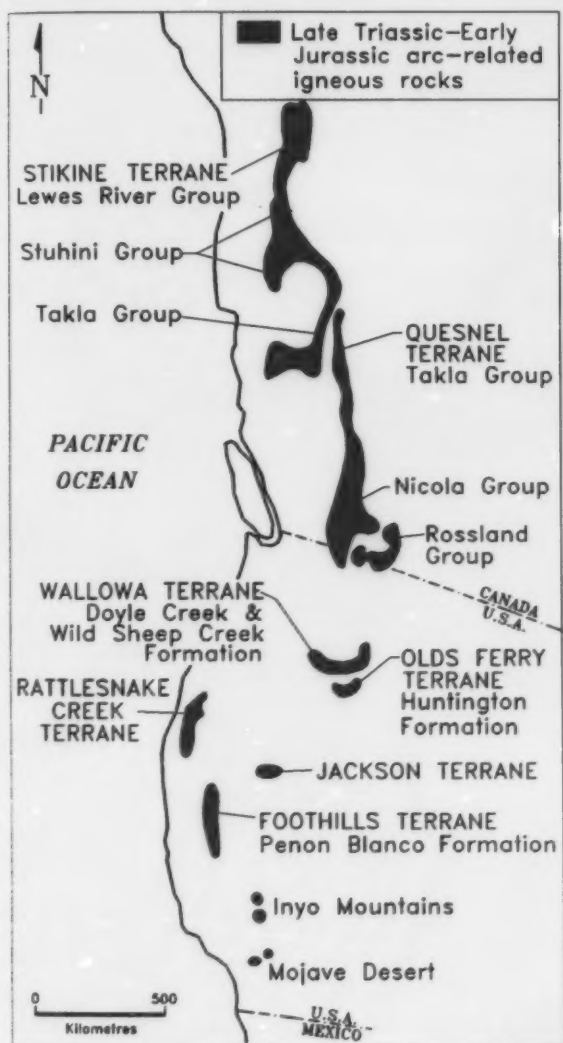


Figure 8-13. Distribution of Late Triassic-Early Jurassic arc-related rocks favorable for gold skarns in North America. (From Ray, 1990, adapted from Mortimer, 1986.)

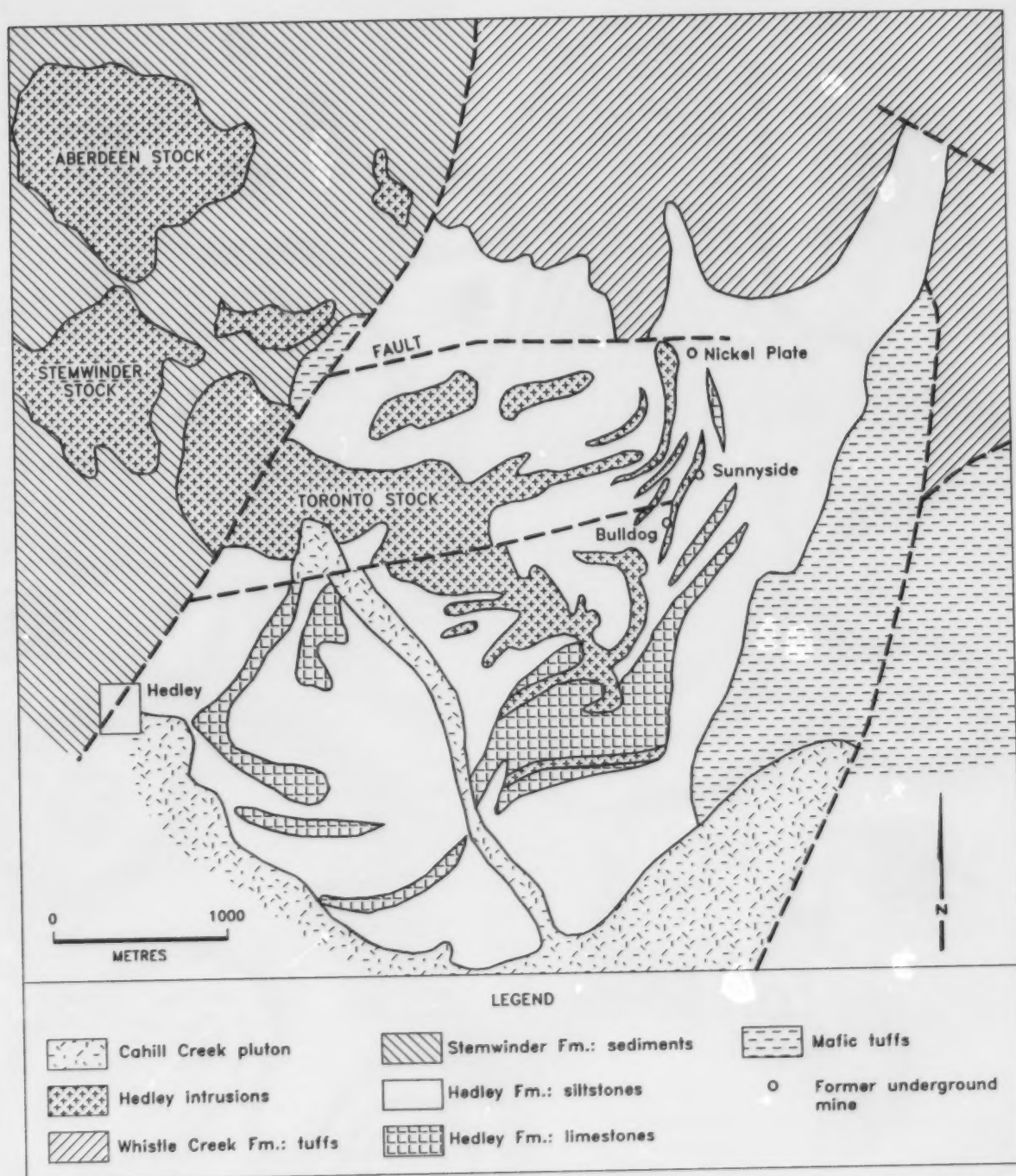


Figure 8-14. Geology of the Nickel Plate mine area (after Ray and Dawson, in preparation). *NOTE:* The Early Jurassic Toronto stock and its associated sill-dike swarm intruded calcareous siltstone and limestone of the Late Triassic Nicola arc.

tion state that occur with increasing skarn overprinting. Initiation of barren skarn alteration causes little change in the total iron content of the endoskarn compared to the unaltered intrusions (average total iron contents of unaltered diorite and weakly altered endoskarn are 7.8 per cent and 6.7 per cent respectively). However, it is marked by an immediate and dramatic change in the oxidation state; $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios average 0.24 in the unaltered intrusions and 0.05 in the weakly to moderately altered endoskarn. This suggests that the skarn-forming fluids at Nickel Plate were highly reduced. More intense alteration in endoskarn adjacent to the ore zones is marked by no further change in the oxidation state, although it is accompanied by a major decrease in the total iron content (Figure 8-17A).

To summarize, the onset of skarn alteration in the endoskarn at Nickel Plate was accompanied by a major change in oxidation state. This suggests the skarn forming fluids were highly reduced and that they caused sulfidation resulting in the crystallization

of pyrrhotite and arsenopyrite. Less dramatic changes in oxidation occurred in the exoskarn because the unaltered sediments have exceedingly low $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios (Figure 8-17B). However, a progressive increase in skarn alteration, accompanied by sulphide-gold mineralization, is marked by a sharp decrease in the iron content of the endoskarn and a corresponding increase of iron in the adjacent exoskarn (Figures 8-17A and 17B). This suggests the Hedley intrusions were the source of the iron enrichment in the exoskarn, and thus may also be the primary source of the skarn-hosted gold.

PROBLEMS IN CLASSIFYING GOLD AND PME SKARNS

Base and ferrous metal skarns have been classified using a number of criteria, including the predominant metal commodity present (Burt, 1972; Einaudi *et al.*, 1981). Likewise, skarns containing gold as the predominant or only economic mineral are classed as gold skarns. However, these skarns are more difficult to classify. Unlike base and ferrous metals, which are commonly present in percentage quantities, gold is a high-value commodity that generally reaches concentrations of only a few parts per million. Thus, small changes in either gold concentration or metal prices can progressively alter the classification of a deposit from an end-member ferrous or base metal skarn to an end-member gold skarn. An example of this is the Phoenix deposit in southern British Columbia, which on the value of its total produced metal (250 000 tonnes of copper, 30.4 tonnes of gold and 194 tonnes of silver) was, throughout most of its history, a PME-copper skarn. However, for short intervals since 1971, when gold prices rose relative to copper, gold would have been the deposit's predominant economic metal; during these times Phoenix would theoretically represent a gold skarn. Moreover some calcic iron skarns, such as the Merry Widow deposit on Vancouver Island (Ray and Webster, 1991) which are being explored for their gold content, also illustrate the problem in classification using a skarn's economic metal content. Nowadays, such deposits would be primarily exploited for their gold rather than the uneconomic magnetite; thus they would theoretically be classed as gold skarn deposits, although they have major mineralogical differences with true gold skarns, such as the Hedley deposits. A continuum probably exists between end-member gold skarns such as the Nickel Plate and Fortitude deposits, and end-member copper and calcic iron skarns with little or no precious metal enrichment.

One method of broadly distinguishing and classifying gold, copper and iron skarns is by comparing their $\text{Cu}:\text{Ag}$ versus $\text{Cu}:\text{Au}$ ratios (Ettlinger and Ray, 1989; Ray *et al.*, 1990). Gold skarns tend to have $\text{Cu}:\text{Ag}$ and $\text{Cu}:\text{Au}$ ratios less than 1000, while copper skarns have $\text{Cu}:\text{Au}$ ratios ranging mainly between 1200 and 25 000, and $\text{Cu}:\text{Ag}$ ratios ranging

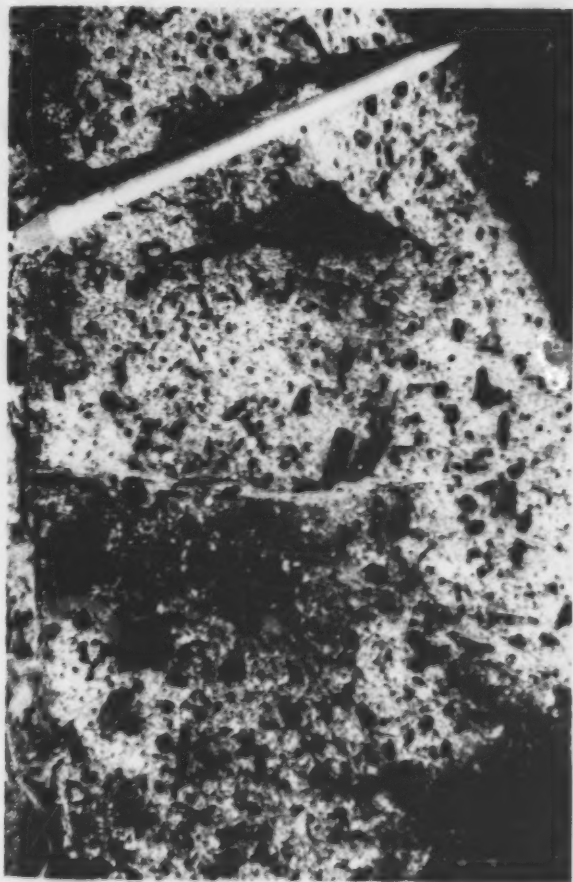


Plate 8-6. Porphyritic intrusion associated with the Nickel Plate gold skarn. Hedley diorite with phenocrysts of hornblende and zoned plagioclase. Hedley, B.C.

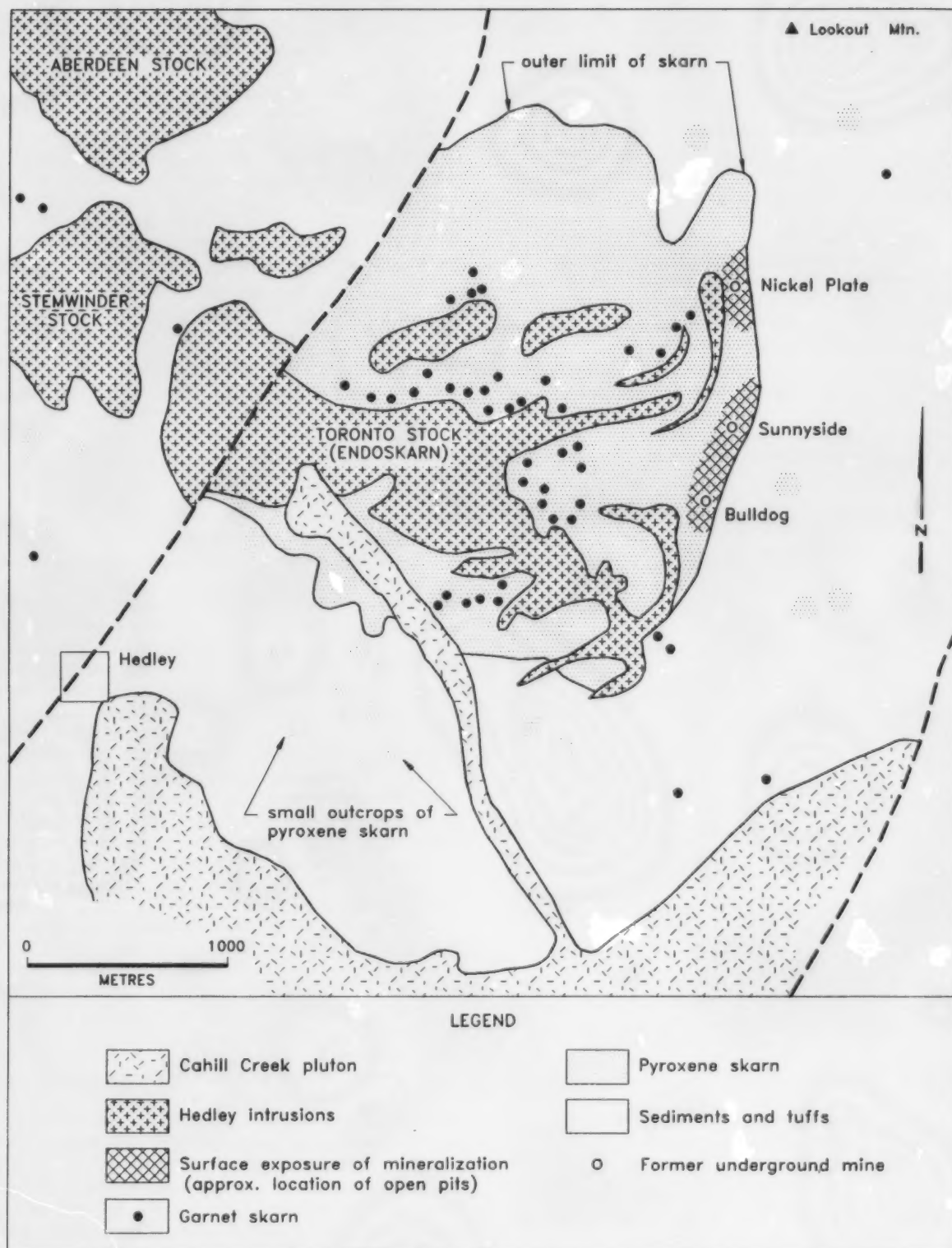


Figure 8-15. Outcrop distribution of the Nickel Plate skarn envelope (after Ray and Dawson, in preparation)
 NOTE: Mineral zoning with extensive distal pyroxene skarn and minor proximal garnet-rich skarn. The envelope covers a 4 square kilometre area and reaches 300 metres in thickness. Mineralization is concentrated close to the base of the westerly dipping skarn, and consequently outcrops along the skarn's eastern margin.

from 500 to 2500. In contrast iron skarns generally have the highest Cu/Au and Cu/Ag ratios, ranging from 20 000 to 160 000 and 2500 to 5 000, respectively.

EXPLORATION CRITERIA FOR GOLD AND PME SKARNS

The worldwide spatial and temporal association between gold skarns, Phanerozoic mobile belts, oceanic island-arc assemblages and porphyry copper districts outlines potential areas for gold exploration in skarn. Besides the relatively well known North American Cordillera, the porphyry copper belts of the Appalachians, South America, the Himalayas, U.S.S.R., Iran and southeastern Asia can be expected to contain gold skarns, particularly where carbonates and oceanic island arc related intrusions are present. Since over 90 per cent of the skarn-related gold in British Columbia has come from the

Triassic island-arc Quesnel Terrane, it suggests that correlative rocks elsewhere in the province and in the North American Cordillera have excellent exploration potential for gold skarns. The location of these correlative rocks is shown in Figure 8-13; they include rocks of the Stikine Terrane in northern British Columbia as well as other Triassic island arcs in the U.S.A.

Gold skarns preferentially develop where intrusions derived from primitive oceanic crust (marked by dioritic composition, high iron content, low $\text{Fe}_2\text{O}_3:\text{FeO}$ ratios and low to intermediate $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios) intrude calcium carbonate rich sequences. Dolomitic or platformal continental carbonate assemblages are less suitable for gold skarn development, probably because they are deposited in regions where oceanic-crust-derived intrusions are not usually generated. However, the OK Tedi PME skarn of Papua New Guinea is an exception as it is hosted in platformal sediments (Barnford, 1972; Davies *et al.*, 1978); this emphasizes that all skarns, irrespective of their mineralogy and tectonic setting, should be routinely assayed for gold.

Because extensive carbonates are uncommon in oceanic island arcs, the most favourable geological environment for gold skarn formation are on the margins of fore or back-arc basins where reefs or carbonate aprons were more likely to have been laid down (Figure 8-3). Rifted back-arc basin margins are also favourable because the controlling structures may preferentially channel the plutons into suitably reactive carbonates. Thus exploration for gold skarns should be directed to areas with:

- Impure, carbonaceous and permeable carbonate sequences in mature island arcs. The presence regionally of limestone gravity-slide breccias (indicating unstable basin margin facies) and potassium-rich volcanics (shoshonites), as seen in Quesnellia, is advantageous.
- High to intermediate-level, arc-related, iron-rich dioritic to gabbroic intrusions with amphibole and plagioclase phenocrysts (Plate 8-6), low to intermediate $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios and low $\text{Fe}_2\text{O}_3:\text{FeO}$ ratios.
- Occurrences of either porphyry copper mineralization, mesothermal veins, epithermal systems, sediment-hosted gold, or iron and copper skarns. A model explaining the common spatial association between these styles of mineralization is outlined by Sillitoe and Bonham (1990).

Economic mineralization in gold skarns generally only forms a small proportion of the total alteration envelope, and ore may be visually indistinguishable from waste. Thus, skarns containing any of the following features should be carefully examined for their gold potential:

- Large, pyroxene-dominant exoskarn envelopes.
- Reduced mineral assemblages with high pyrrhotite:pyrite ratios.

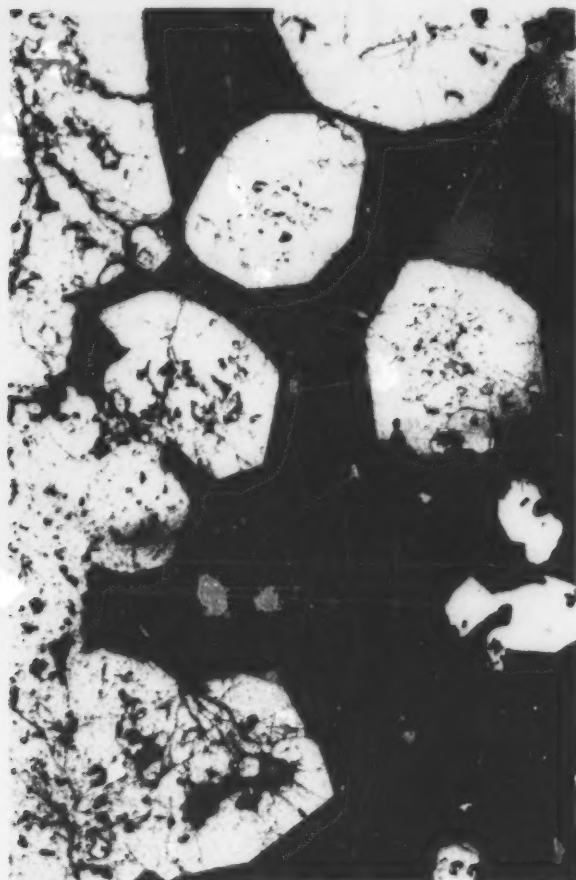


Plate 8-7. Photomicrograph (PPL) of euhedral andraditic garnet crystals enclosed by sulphides. The latter includes chalcopyrite, arsenopyrite and pyrrhotite with trace tellurides and gold. French mine gold skarn, Hedley, B.C. Field of view is 3 millimetres top to bottom.

- The presence of an early phase of potassic alteration (biotite, orthoclase) that predates the pyroxene-garnet skarn assemblages.
- The presence of tellurides.
- Geochemical enrichment in tellurium, bismuth, arsenic, selenium or cobalt.
- Presence of scapolite or chlorine-rich amphiboles.

Initial exploration of a skarn for gold should involve both geochemical sampling, using bismuth, tellurium, arsenic and cobalt (and gold) as pathfinder elements, and geological mapping to delineate the zones of prograde and retrograde alteration. Core logging should be conducted only by staff experienced in skarn mineralogy; care should be taken to look for scapolite and tellurides, and the mineral paragenesis should be determined to aid mapping.

It should be noted that at Nickel Plate, the mineralization, which lies close to the base of the envelope, is mostly overlain by 200 to 300 metres of barren skarn. Consequently, surface exposure of mineralization in some skarns may depend on the level of erosion, and deeply buried blind orebodies may be common. Because this upper, barren skarn is rela-

tively impervious to geochemical dispersion, deep drilling with down hole geophysics may be necessary to determine whether the base of the skarn is mineralized. In Saskatchewan, geobotanical sampling was employed to locate blind uranium orebodies (Dunn, 1981); similar techniques could perhaps determine the presence of deeply buried gold skarn deposits.

SKARNS IN BRITISH COLUMBIA

DISTRIBUTION OF OCCURRENCES AND DEPOSITS

British Columbia possesses important iron, copper and gold skarn deposits, but has had no tin production and only minor production of tungsten, lead-zinc and molybdenum from skarn. At least 628 mineralized skarn occurrences are listed in the MINFILE database. Of these, 91 of the 116 past or present producers have recorded production data (Table 8-6). The distribution of the skarn occurrences and producing deposits in relation to the five tectonic belts in the province is shown in Figures 8-9 and 11. Figure 8-9 clearly illustrates that all of the major producing skarn deposits are located close to either

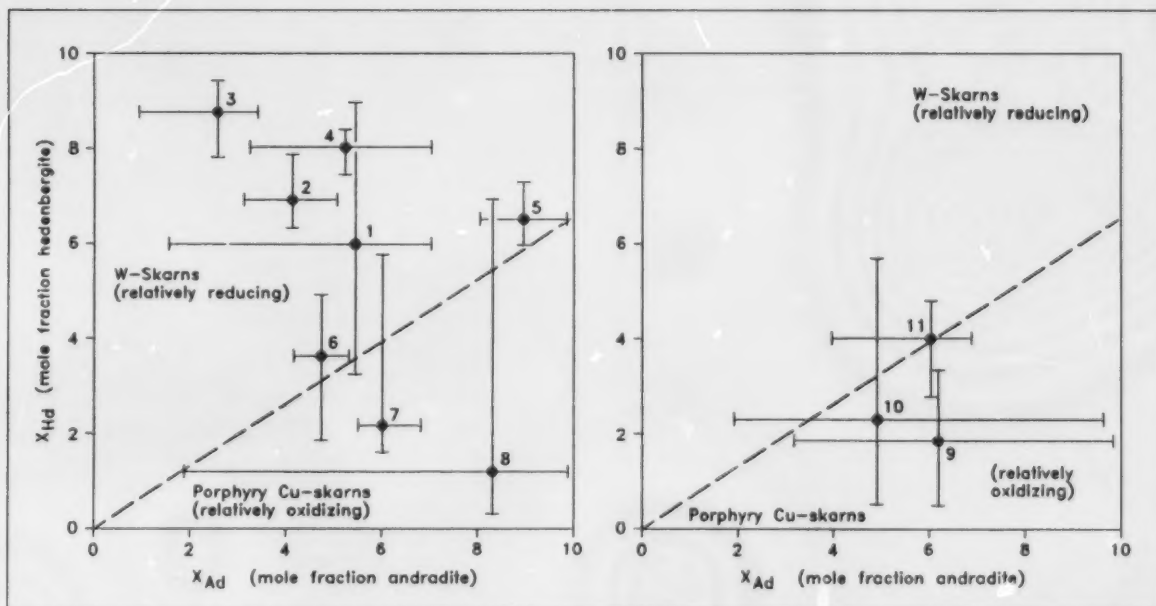


Figure 8-16. Plot of mole fraction hedenbergite (Hd) versus mole fraction andradite (Ad), illustrating the relative oxidation states of some gold, PME-copper and PME-iron skarns. Upper left field=relatively reducing W-skarms, lower right field=relatively oxidizing porphyry copper skarns, after Einaudi, (1982); (plot made on two diagrams due to density of data): 1=Nickel Plate (Au), Hedley, BC; 2=Canty (Au), Hedley, BC; 3=Good Hope (Au), Hedley, BC; 4=Peggy (Au), Hedley, BC; 5=French (Au), Hedley, BC; 6=Bob skarn (Au), Banks Island, BC; 7=TP skarn (Au), Atlin, BC; 8=Red Dome (Cu, Au), Australia; 9 and 10=Little Billie (Cu,Au) and Florence (Au,Cu), Texada Island, BC; 11=Texada Iron (Fe,Au), Texada Island, BC. Note relatively reduced states for the Hedley gold skarns and oxidized to intermediate states for the TP gold skarn and the PME skarns at Red Dome and Texada Island. Data for 1 to 7 and 9 to 11 from Ettlinger and Ray (1989) and Ray and Dawson, (in preparation), for 8 from Eweres (personal communication, 1988) Bar lines show range of X_{Hd} and X_{Ad} values; centre dots=mean values.

the U.S. border or the coast where access is easier and past exploration has been greater. This emphasizes that the least explored northern parts of British Columbia have good potential for containing economic skarn deposits, particularly gold and copper skarns.

The Insular Belt has the most skarn occurrences but the majority of producing deposits are found in both the Insular and Omineca belts. The Coast Belt is comparatively poorly represented in skarn occurrences and deposits (Figure 8-11), while the Foreland Belt, despite extensive platform carbonates and some intrusions, has virtually no skarns.

METAL PRODUCTION FROM SKARN

A compilation of the province's metal production from skarn is outlined in Table 8-7, together with the total metal production from all bedrock sources.

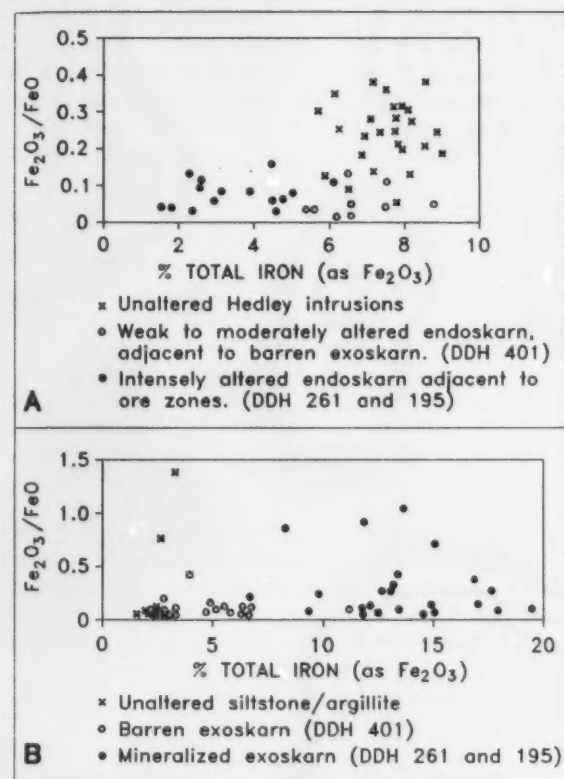


Figure 8-17. Plots comparing $\text{Fe}_2\text{O}_3/\text{FeO}$ vs. total iron (expressed as Fe_2O_3) of unaltered Hedley intrusions with endoskarn (A), and unaltered sedimentary rocks with exoskarn (B) at the Nickel Plate deposit.

A. NOTE: Low ferric/ferrous ratios in weakly altered, barren endoskarn, compared to unaltered intrusions, together with the lower iron content of the intensely altered endoskarn adjacent to ore zones.

B. NOTE: Progressive increase of total iron in exoskarn with increasing skarn alteration.

Skarn has been the major producer of iron, and accounts for 88 per cent of the total mined; minor past production from limonitic sediments has also occurred in British Columbia as well as the manufacture of some pig iron from calcined iron sulphide stockpiles at the Sullivan Pb-Zn mine.

Skarn has also been an important source of tungsten (82%), gold (16%) and copper (12%). However, the total tonnage of tungsten mined is relatively small; it was obtained mainly from several deposits in the Salmo mining camp, of which the Emerald Tungsten mine was the largest. Skarns in British Columbia have been unimportant as a source of lead, zinc, molybdenum and silver, and no skarn-derived production of tin has occurred (Tables 8-6 and 8-7).

The skarns of British Columbia have produced approximately 101 tonnes of gold (Tables 8-6 and 8-7). Of this, 53 per cent was derived from gold skarns, whereas 40 per cent and 7 per cent respectively were obtained as byproducts from copper and iron skarns. Although over 64 skarns in the province have produced some gold, more than 90 per cent of the production came from just 8 deposits. The Nickel Plate gold skarn and Phoenix PME-copper skarn make up the major portion of gold production (80 per cent), but other important producers include the Motherlode, Tasu, Old Sport, Marble Bay, French and Second Relief deposits (Figure 8-9).

Approximately 360 tonnes of silver has been produced from skarn although this represents less than 2 per cent of the province's total silver production (Table 8-7). All the silver from skarn was derived as a byproduct; copper and iron skarns account for most of the silver (68 and 27% respectively) while the gold skarns have produced less than 2 per cent (Ettlinger and Ray, 1989). The single largest source was the Phoenix PME copper skarn which accounted for over 50 per cent of the skarn-derived silver (194 tonnes).

The skarn related metal production from each tectonic belt is illustrated in Figure 8-12. A close spatial association between certain metals and particular belts is demonstrated. Most iron has come from the Insular Belt and nearly all of the magnetite-rich iron skarn deposits are hosted in Late Triassic volcanic-limestone sequences in the Wrangellia Terrane. The minor amount derived from the Intermontane Belt was obtained as a byproduct from the Craigmont copper skarn.

There is a tendency for iron, copper and gold to be concentrated in the tectonic terranes dominated by oceanic crust, while most of the skarn-derived lead, zinc, tungsten and molybdenum production has come from the continental crust or platformal sediment-dominant terranes farther east. There has been no metal production from the Foreland Belt and virtually none from the Coast Belt. As the latter contains abundant intrusions and some carbonate-bearing roof pendants, the reason for its comparative

lack of skarns is unclear; this suggests the existence of some fundamental metallogenic difference between the Coast Belt and the adjoining Insular and Intermontane belts.

Gold and copper from skarn were overwhelmingly derived from Late Triassic volcanic island-arc assemblages of the Quesnel Terrane of the Intermontane and Omineca belts. Most of the comparatively minor gold and silver production from the Insular Belt was obtained as a low-grade byproduct from the iron skarns. Although there is a correlation between gold and copper in Quesnellia rocks of the Intermontane and Omineca belts (Figure 8-12), these metals are not always associated in skarn deposits. Some copper skarns, such as the Craigmont, are gold poor, some gold skarns are relatively barren of economic copper (e.g., Hedley), whereas others such as the Phoenix deposit contain appreciable values of both metals. Nevertheless, the overall terrane control to these metals emphasizes the importance of Quesnellia and correlative rocks elsewhere (Figure 8-13) for gold and copper exploration in skarn.

ACKNOWLEDGMENTS

Much of the data in this paper concerning British Columbia was compiled during an ongoing study of the province's skarns funded by the Canada-British Columbia Mineral Development Agreement 1985-1990. We are grateful for the assistance and constructive comments of A.D. Ettlinger and G.L. Dawson. The cooperation of the management and staff of the following companies are acknowledged: Corona Corporation (formerly Mascot Gold Mines Ltd.), Freeport-McMoRan Gold Company, Echo Bay Mines Ltd., Chevron Minerals Ltd., Esperanza Exploration Ltd., Cordilleran Engineering Ltd., Vananda Gold Ltd. and Banbury Gold Mines Ltd. Editing by J.M. Newell and the constructive suggestions by D.M. Burt of Arizona State University, who externally reviewed the manuscript, are also appreciated.

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PORPHYRY DEPOSITS IN THE CANADIAN CORDILLERA

by W. J. McMillan

INTRODUCTION

Worldwide, porphyry deposits occur in orogenic belts, and many are related to subduction-generated plutonism and volcanism at consuming plate margins. Most occur either in island-arcs or at continental margins. Most are Mesozoic or Cenozoic but older examples occur.

In the Canadian Cordillera, porphyry deposits are characteristic in the Intermontane Belt and also occur in the Insular Belt (Figure 9-1). Excellent detailed information about these porphyry copper and porphyry molybdenum deposits is provided by papers in Canadian Institute of Mining and Metallurgy, Special Volume 15, *Porphyry Deposits of the Canadian Cordillera*, edited by Atholl Sutherland Brown and published in 1976.

In the present economic climate, combined base and precious metal deposits present attractive exploration targets. Fortunately, significant gold and silver values characterize many porphyry copper deposits in the Canadian Cordillera. Schroeter *et al.* (1989) and Schroeter and Lane (1991) compiled production and reserve statistics. In 1988, more than half the province's gold reserves and 80 per cent of the province's copper reserves were in porphyry deposits (Figure 9-2a). The gold figures represent a swing away from historical production patterns (Figure 9-2b); this swing started in the late 1950s when the province's first porphyry copper mines were put into production (Figure 9-2c). In 1990, 21 per cent of the gold and 15 per cent of the silver produced in British Columbia was byproduct from base metal porphyry deposits, some of which rank with the largest lode-gold deposits in the province (Figure 9-3). Gross value of production of all metals from porphyry deposits in British Columbia was \$950 million (Canadian) in 1988, \$847 million in 1989 and about \$1028 million in 1990. Today, exploration for copper-gold porphyries is in high gear.

This paper focuses on characteristics of porphyry copper and copper-gold rather than porphyry molybdenum deposits, which are well described in CIM Special Volume 15. It attempts to introduce most of the major questions about porphyry copper deposits and to present ideas for exploration. The definition of the term "porphyry deposit" will be considered first, then the distribution, ages and regional tectonic settings of these deposits. Classification schemes will be described, the characteristics of related intrusive rocks, alteration and mineralization

types outlined, and the genesis of porphyry deposits discussed. Mainly Cordilleran examples will be used to illustrate the characteristics of these fascinating deposits.

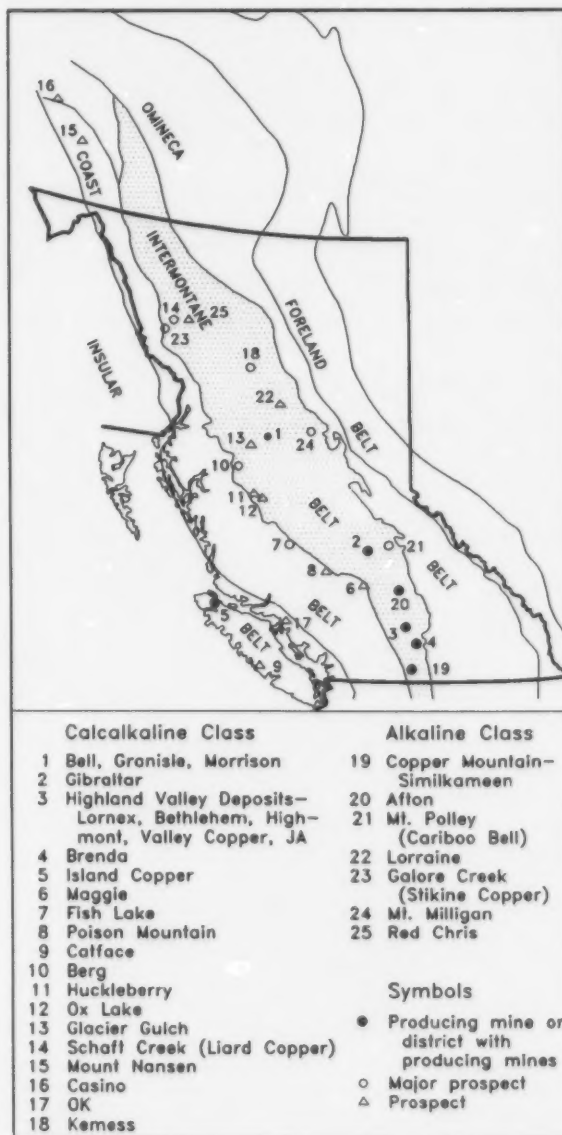
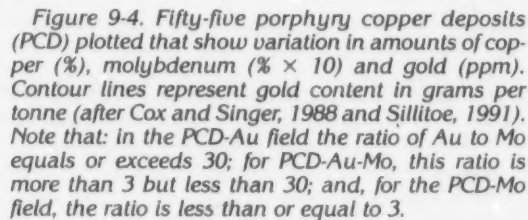
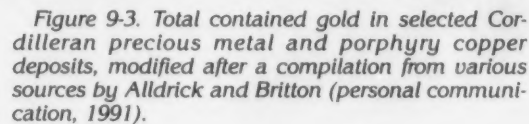
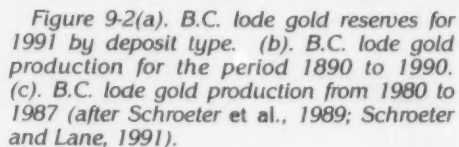


Figure 9-1. Distribution of porphyry copper deposits relative to tectonic belts in the Canadian Cordillera.



DEFINITION OF THE TERM PORPHYRY DEPOSIT

The definition of the term porphyry deposit is based partly on geology and partly on engineering practices. No single criterion adequately defines porphyry deposits but they have characteristics in common:

- Mineralization is widely dispersed in porphyritic intrusions or adjacent country rocks.
- Grades are generally low and the deposits are mined by large tonnage, low unit cost methods.
- The tie to intrusive rocks is both spatial and genetic.
- Most of the related intrusives are calcalkalic to alkalic, epizonal and porphyritic.
- Typical related porphyritic host rock suites are granodiorite to granite or diorite to syenite.
- Intrusives with porphyry molybdenum deposits tend to be calcalkalic and felsic.
- Multiple intrusions are characteristic but mineralization relates to specific intrusive episodes.
- Dike swarms and breccia pipes, frequently with milled clasts, typically accompany mineralization.
- Both the intrusions and the country rock are strongly and pervasively fractured.
- Most mineralization is fracture controlled but disseminated mineralization is important in some deposit classes.
- Alteration is widespread and zoned, although it varies in type and extent of development.
- In some areas, weathering with supergene alteration and enrichment are important factors.
- Size is an important part of the definition: the deposit must contain at least 20 million tonnes of at least 0.1 per cent copper to be classed as a porphyry copper.

The spectrum of porphyry deposit types grades from copper, to copper-molybdenum, to copper-gold-molybdenum, to gold only, to molybdenum only (Figure 9-4). Generally, as the figure shows, gold and molybdenum are negatively correlated, but transitional deposits (Cox and Singer, 1988) exist;

Cordilleran examples are Island Copper and Poison Mountain. These authors tabulated the median sizes, tonnages, depths of emplacement and other features for each subclass of deposit (Table 9-1).

WORLDWIDE DISTRIBUTION OF PORPHYRY DEPOSITS

Around the world Mesozoic and younger mountain belts host porphyry copper deposits. Many are in island-arc rocks and related to high level, calcalkalic or alkalic porphyry intrusions of intermediate composition. In general, most related porphyritic intrusions are Andinotype or I-type, or magnetite series granitic rocks according to classification schemes summarized by Anderson (1988). Most I-type intrusions are subvolcanic, associated with island arc volcanism, gregarious or multiple, of variable size, mainly of intermediate composition but commonly zoned from mafic to felsic, have hornblende and biotite as the more abundant mafic minerals, and have accessory magnetite, apatite, zircon and allanite. Chemically, they contain less than 70 weight percent SiO_2 , are metaluminous, have normative clinopyroxene or corundum, Na_2O exceeds K_2O , TiO_2 is relatively high, they are relatively oxidized, and initial ^{87}Sr to ^{86}Sr ratios are low, from 0.704 to 0.706. According to Sillitoe (1989a), 85 per cent of intrusions with porphyry deposits with gold are at convergent margins above active subduction zones. Often the mineralization is associated with extensional settings in the overriding plates. Magmatism tends to be bimodal, but silicic types predominate. The host rocks for the mineralization may be sedimentary, volcanic or intrusive. In British Columbia, copper grades are notably higher and gold concentrations tend to be higher in deposits associated with alkalic intrusive rocks, but some deposits associated with calcalkalic intrusives are significantly larger (Table 9-2). Elsewhere around the Pacific Rim, porphyry deposits related to calcalkalic rocks not only are large but also have relatively high gold and copper grades (Sillitoe, 1991); thus exploration potential for similar deposits in the Canadian Cordillera is attractive.

Earlier, Sillitoe (1987) pointed out that copper-gold deposits around the Pacific rim form discrete, linear belts. Most are Cenozoic and mineralizing events took place over time periods of 11 to 14 million years. He argues that most of the magmas and metals are derived from the mantle and that neither crustal thickness nor crustal contamination are major factors; for example, he related southwestern U.S. porphyries to a period of rapid, low-angle subduction. However, Titley (1987), who compiled gold and silver values from deposits of all types and ages across Arizona, found that Au:Ag ratios are bimodal. He concluded that these values are not related to subduction, but were inherited from the specific kinds of crust underlying the area. The debate continues.

TABLE 9-1

Median Grades, Tonnages and Depths of Porphyry Copper Deposits

	Porphyry Copper		
	Au type	Au-Mo type	Mo type
Number of deposits	20	19	16
Size (million tonnes)	160	390	300
Copper (%)	0.55	0.48	0.41
Molybdenum (%)	0.003	0.015	0.016
Gold (g/t)	0.38	0.15	0.012
Silver (g/t)	1.69	1.63	1.22
Magnetite (%)	2.6	1.0	0.05
Depth (km)	1.0	0.9	3.6

(after Cox and Singer, 1988)

TABLE 9.2

Size, Grade and Gold Content of Selected Canadian Cordilleran Porphyry Copper Deposits

ALKALIC CLASS						
Deposit	Type	Size	Copper (%)	Recovered	Gold (g/t) Contained	Contained Gold (tonnes)
Afton/Ajax	V	66.0	0.77	0.460	0.560	37.0
Mount Polley	V	48.0	0.44	—	0.583	28.0
Kerr	V	114.0	0.61	—	0.270	30.8
Lorraine	V	9.1	0.70	—	0.343	3.1
Mount Milligan	V	417.0	0.22	—	0.490	204.3
Red Chris	V	41.0	0.56	—	0.320	13.1
Copper Mountain	V	32.0	1.08	0.190	—	6.1
Similco/Ingerbelle	V	141.0	0.47	0.130	—	18.3
Galore Creek	V	125.0	1.06	—	0.400	50.0
CALCALKALIC CLASS						
Schaft Creek	V	910.0	0.30	—	0.11–0.34	100–300
Morrison	C	38.0	0.42	—	0.300	11.4
Kemess North	C?	141.0	0.17	—	0.330	46.5
Kemess South	C?	171.0	0.23	—	0.630	107.7
Berg	C	238.0	0.39	—	0.050	11.9
Granisle	C	52.0	0.41	0.090	0.120	6.2
Bell Copper	C	67.0	0.47	0.170	0.350	23.5
Fish Lake	C	477.3	0.20	—	0.380	181.4
Poison Mountain	C	159.0	0.33	—	0.310	49.3
Hushamu (Expo)	V	97.0	0.29	—	0.340	33.0
Island Copper	V	257.0	0.52	0.110	0.220	56.5
Red Dog	V?	45.0	.32	—	0.410	18.5
Catface	C	151.0	0.43	—	0.05(est.)	uncertain
Gibraltar	P	413.0	0.35	—	0.007	2.9
Brenda	P	164.0	0.16	0.0140	0.031	5.1
Lornex	P	577.0	0.39	0.0005	0.006	3.5
Bethlehem	P	144.0	0.50	0.0120	0.013	1.9
Valley Copper	P	576.0	0.48	0.0005	0.006	0.9
Hightmont	P	123.0	0.25	—	0.006	0.7
JA	P	286.0	0.43	—	unknown	unknown

(after Schroeter *et al.*; CIM Special Volume 15; Panteleyev, personal communication, 1991; and various other sources).

C = Classic
V = Volcanic
P = Plutonic
est. = estimate

AGES OF INTRUSION AND MINERALIZATION

World-wide, the oldest deposits known that are clearly porphyries are Paleozoic albeit some Precambrian deposits have been classified as porphyries. However, the majority are Mesozoic and Tertiary and the youngest, in New Guinea, is about 1 million years old.

Multiple magmatic events characterize porphyry districts. Mineralization often follows one or more pulses of magmatism and may be followed by barren magmatic pulses; more than one pulse can have related mineralization. In general, copper mineralization accompanies one of the youngest intrusive phases. At Ray, Arizona, for example, the oldest intrusive is 70 Ma and porphyry was intruded at 63 Ma, but mineralization accompanied 61 Ma intru-

sions (Cornwall and Banks, 1977). Similarly, at OK Tedi (Page, 1975) mineralization occurred 1 to 3 million years after emplacement of the initial magma.

In the Canadian Cordillera, most porphyry deposits are in island arc rocks of the accreted Intermontane Superterrane, some are in the Insular Superterrane (Figure 9-1). Deposits associated with calcalkalic intrusions are of Mesozoic to Tertiary age; those related to alkalic intrusions are Early Jurassic and generally have related shoshonitic volcanism (Barr *et al.*, 1976). However, some porphyry deposits are post-accretionary. They are related to calcalkalic intrusions along transverse structural zones like the Stikine and Skeena arches, or are in Tertiary extensional settings; examples are Bell and Granisle in central British Columbia. Gold values can be relatively elevated in deposits related to both



Figure 9-5. Distribution of porphyry copper deposits in the Canadian Cordillera identifying those related to calkalkalic and alkalic intrusions.

alkalic and calkalkalic intrusions (Figure 9-5), as is evident for deposits around the Pacific rim, and in British Columbia (Figure 9-6, Table 9-2).

DEPTH OF EMPLACEMENT

Most porphyry systems are related to plutons emplaced at relatively shallow depths. Reconstructions and geological mapping indicate a maximum depth of about 4 kilometres and a typical depth of 2 kilometres (Sutherland Brown, 1976). The porphyry intrusions are injected as crystal-liquid mixtures that evolve aqueous fluids as the magma crystallizes and confining pressure decreases during magma ascent. Sudden cooling and release of volatiles due to the change from lithostatic to hydrostatic pressure at the emplacement level leads to formation of large hydrothermal systems with resultant large alteration halos, hydrothermal brecciation, and intense fracturing in and around the intrusions. In some cases, the intrusions apparently were saturated or oversaturated with water before they were emplaced at higher levels, which would promote these processes. Incorporation of wallrock fluids, resulting from metamorphic dewatering or deep groundwater circulation, further enhances these processes.

CHARACTERISTICS OF ASSOCIATED INTRUSIVE ROCKS

According to Strong (1988) some of the variations in metal concentrations in granitic melts are related to magma source rocks, water content and depth of emplacement. Lithophile elements (Figure 9-7) tend to form ionic bonds and become concentrated in

silicic melts formed by magma fractionation or partial crustal melting. Chalcophile elements, because they tend to form covalent bonds with oxygen, are excluded from silicate lattices and concentrate in the remaining melt. Ionic bonding characterizes tungsten, tin and molybdenum, whereas covalent bonding is typical of copper and gold; zinc and lead have intermediate characteristics. Strong argues that either granophile or porphyry deposits will form (Figure 9-8) depending, in part, on the type of material melted, the water content of the melt, and its depth of formation along a subduction zone. Porphyry deposits are associated with I-type, biotite or hornblende granites produced by magmatic fractionation, which, because they are relatively hot and dry, intrude to shallow levels in the crust before they solidify. In contrast, granophile deposits occur in association with S-type muscovite granites, produced by anatexis melting, which, because they are cooler and wetter, solidify deeper (12–16 kilometres) than the I-type granites. Mutschler and Mooney (in press) emphasize that many major alkaline provinces are associated with mantle hot spots in cratonic interiors, along passive continental margins, and in back-arc plate margin settings. They comment further that underplating of the basaltic magmas produced can trigger partial crustal melting to produce calkalkalic magmas and stress the exploration potential of hot spot sites and tracks.

If elements like copper behave incompatibly with respect to silicate minerals, they remain in the residual melt and gradually become more concen-

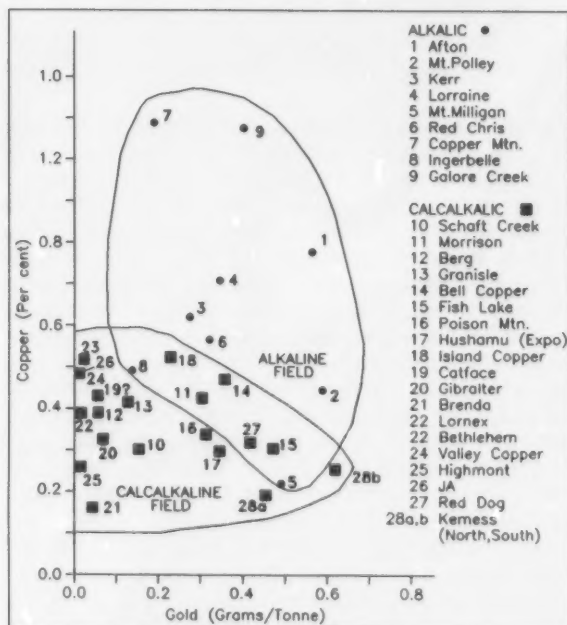


Figure 9-6. Gold plotted against copper values for porphyry deposits in British Columbia (after Schroeter, et al., 1989). See Figure 9-5 for locations.

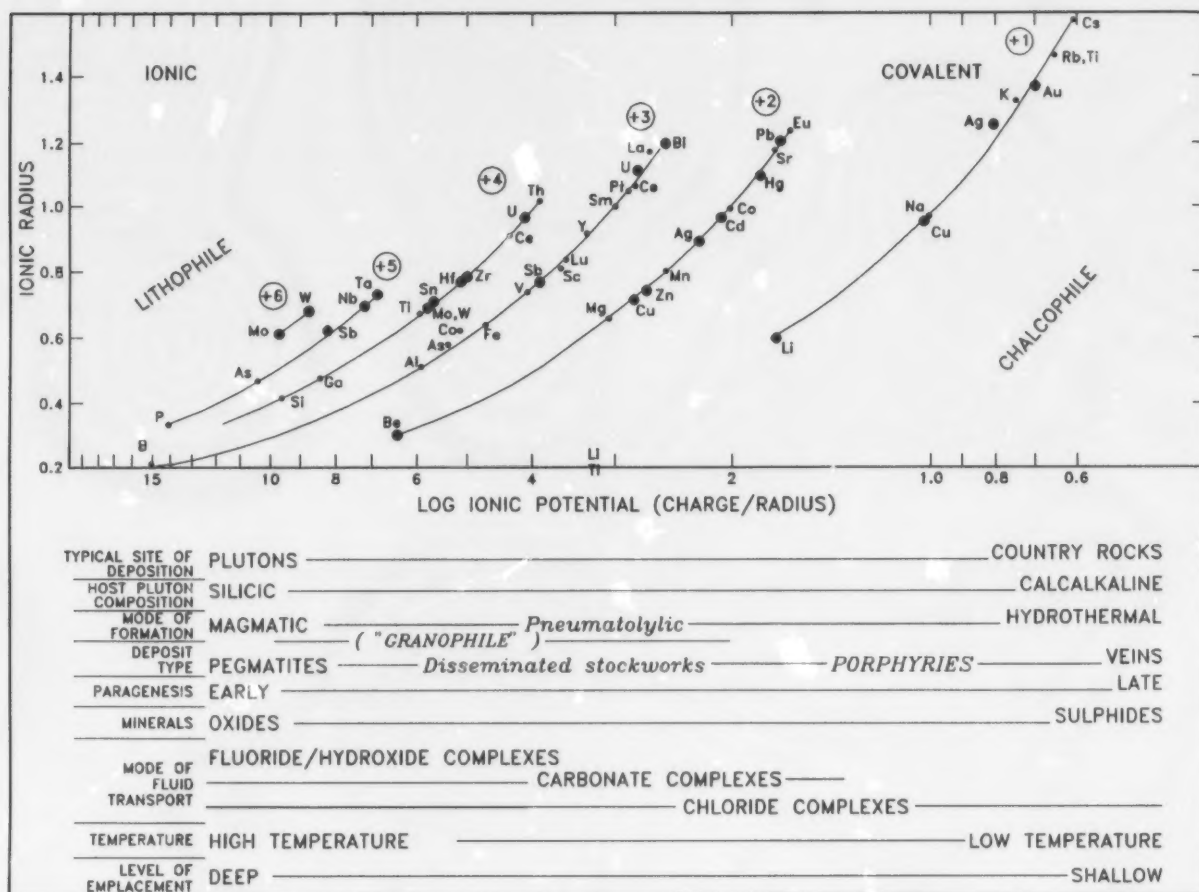


Figure 9-7. Schematic outline of ionic radius and ionic potential, two of the many variables that affect the geochemical behavior of elements in granitoid ore deposits (after Strong, 1988).

trated. Similarly, if vapour "boils off" from the magma, remaining aqueous fluids will be metal-rich, concentrated brines. For example, copper acts as an incompatible element in I-type intrusions because aluminum is enhanced relative to total alkalis and potassium is relatively depleted. This may explain why porphyry coppers so often are related to island arc granites. Cline and Bodnar (1991) carried out numerical simulations of chlorine and copper partitioning between a crystallizing melt and exsolving aqueous fluids. Their data indicates that "typical" calcalkaline magma contains sufficient copper, chlorine and water to produce economic porphyry copper mineralization. The most important variables are the degree of compatible behavior displayed by copper, the ratio of initial water in the melt to the water saturation level, and the initial Cl/H₂O ratio in the melt. Melts with initial water concentrations of at least 2.5 weight per cent water and Cl/H₂O as low as 0.03 can produce economic deposits from less than 30 cubic kilometres of melt if copper behaves incompatibly prior to water saturation, or if the initial melt is water-rich.

Copper is also incompatible in continental-margin S-type granites. The reason, however, is different. Copper in potassium-rich, S-type intrusions behaves incompatibly because they have high oxygen fugacity and high partial pressures of water (Mason and Feiss, 1979). Where hydrothermal fluids are present, the volatiles and metals partition into them.

The relationship between subduction and porphyry deposits in British Columbia was tested by comparing the distribution of Early Jurassic and Early Tertiary granitic rocks in the Canadian Cordillera (Woodsworth *et al.*, 1989) and their initial strontium ratios (Armstrong, 1988; Figure 9-9a,b). Many porphyry-related plutons lie close to the line that marks intrusions with initial ⁸⁷Sr/⁸⁶Sr values below 0.704, that is, I-type granites derived from the mantle or subducted oceanic crust. Porphyry deposits are virtually confined to areas where intrusions have primitive strontium ratios and are hosted by granitic rocks that show no signs of crustal contamination. On the other hand, molybdenum, tin and tungsten deposits tend to occur with more crustally contaminated and evolved melts.

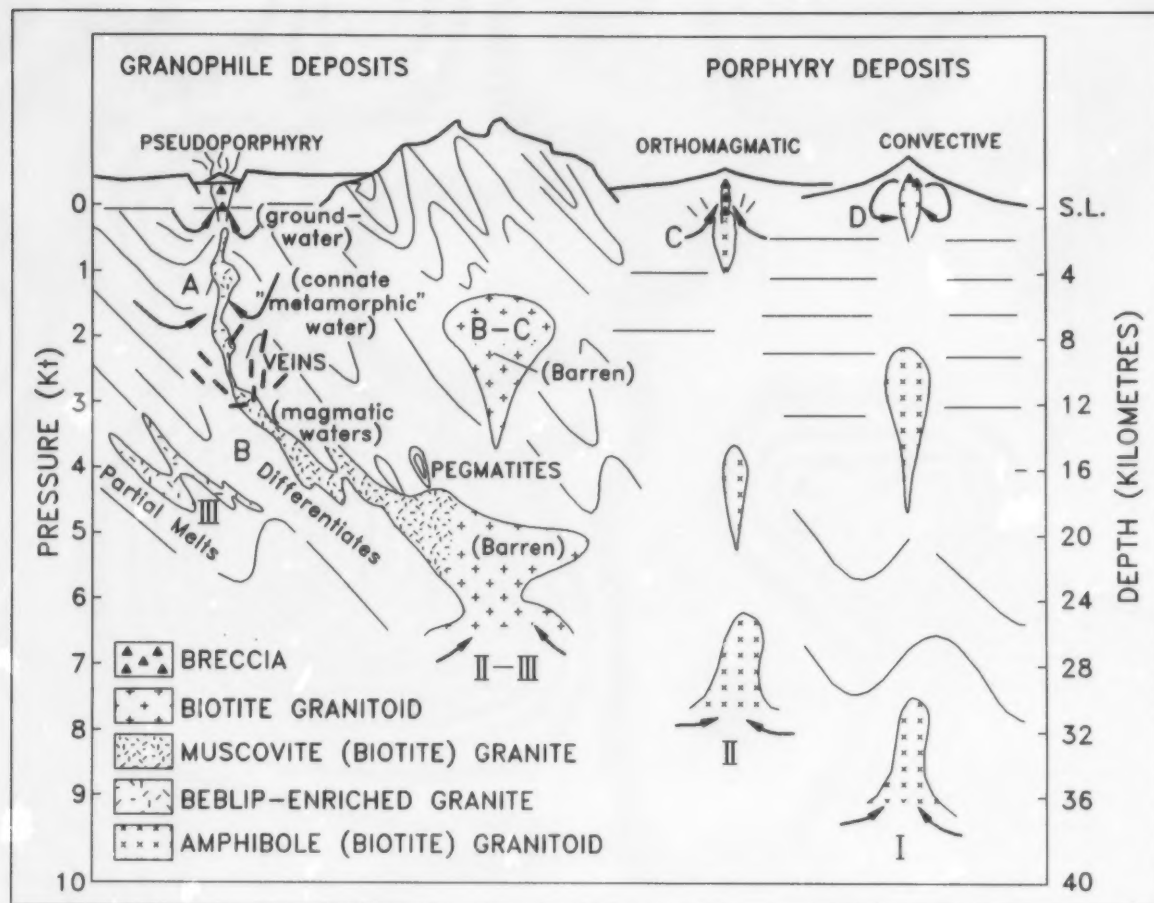


Figure 9-8. Schematic representation of typical settings for granophile-enriched and porphyry-related granitoids. Note: BEBLIP is an acronym for the elements Beryllium, Boron, Lithium and Phosphorous (after Strong, 1988).

ALTERATION IN PORPHYRY SYSTEMS

Hydrothermal alteration associated with porphyry systems is largely a base leaching process related to hydrolysis that is controlled by the metal ion to hydrogen ion ratio in the altering solution. Influencing factors are pressure and temperature, water to rock ratio and fluid and country rock composition. For example, if the ionic ratio of potassium plus sodium to hydrogen is low, then feldspars, micas and other potassium, sodium, calcium aluminosilicate minerals are unstable and begin to alter (Figure 9-10). Further, magmatic vapour saturation or boiling can lead to formation of acidified solutions that cause argillic alteration; fluid inclusions provide evidence that the solutions are sulphur and chlorine-rich.

Alteration associated with the two main petrochemical classes of porphyry deposits differ somewhat. Calcalkaline deposits have alteration patterns like those described from the southwestern United States: central potassic alteration zones, defined by secondary biotite or metasomatic

potassium feldspars, pass outward through successive envelopes of phyllic alteration, defined by the presence of sericite and quartz, then propylitic alteration, defined by epidote, chlorite and albite, into unaltered rock (Figure 9-11a). Although alkalic deposits also have central potassic or albitic plagioclase alteration zones and flanking, more extensive, propylitic envelopes, these may occur as overlapping stages. Generally alteration is patchier and no phyllic zone is developed. According to Lowell (1989) the alkalic deposits tend to have gold-enrichment in the potassic core zones, be related to high-level intrusions, and may have relatively short vertical sections; many have a stubby funnel-shaped-cross section.

Potassic and flanking propylitic alteration form early. In the potassic zone, where near-magmatic conditions exist, all original constituents are unstable. Quartz, biotite, intermediate plagioclase and potassic feldspar are typical alteration products; anhydrite and hornblende occur locally. In the propylitic zone, where alteration occurs under conditions of weak hydrolysis, quartz and potassic feld-

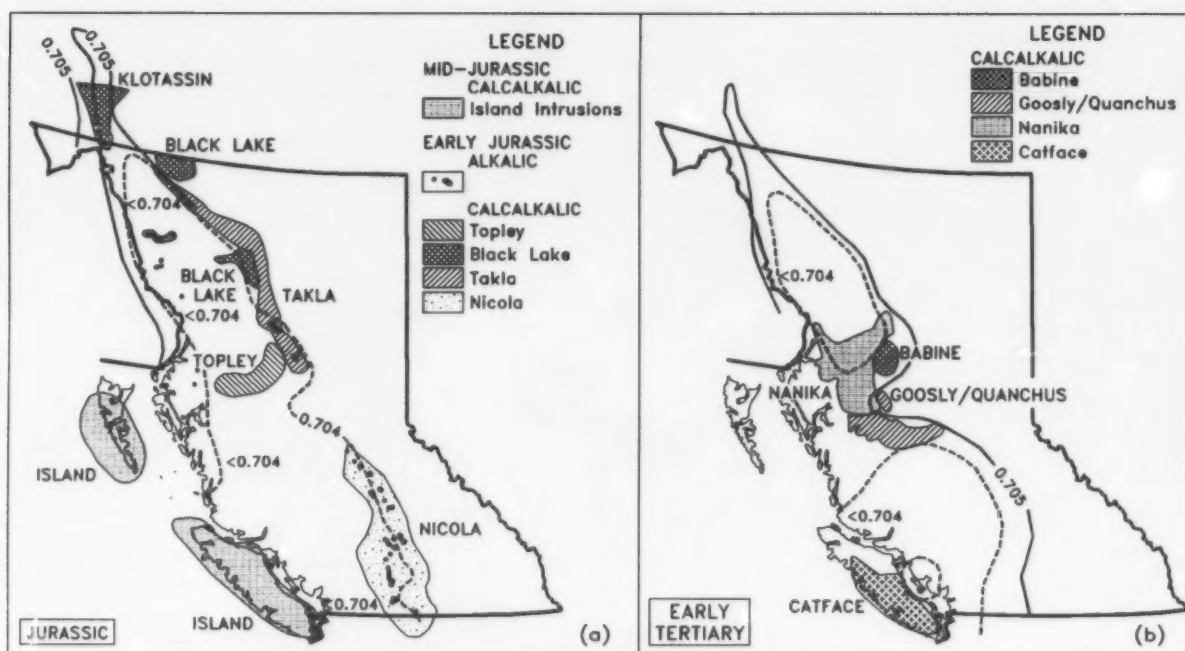


Figure 9-9a,b. Initial strontium ratios for (after Armstrong, 1988) and locations of selected Mesozoic and Cenozoic granitic rocks (after Woodsworth et al., 1989) in the Canadian Cordillera.

spar are stable but plagioclase, which is generally of intermediate composition, alters to a mixture of albite, epidote, carbonate and montmorillonite. Mafic minerals are replaced by chlorite and epidote, or less commonly by actinolite and tremolite. Argillic and phyllic alteration follow and represent increasing intensity of hydrolysis. Argillic alteration results from the formation of quartz, kaolinite, chlorite and lesser mixed-layer clays, it grades into phyllic alteration, which is characterized by the assemblage quartz-sericite-illite-pyrite. In some cases the earlier assemblages are overprinted by assemblages representing intense hydrolysis. Stable phases of this advanced argillic alteration are quartz, pyrophyllite, kaolinite, dickite and sometimes andalusite. In rare examples of very intense argillic alteration, where all other minerals are unstable, the result is a porous mass of quartz.

In an idealized model, the alteration is portrayed as a series of shells around the porphyry intrusion. In reality, it is critical to remember that hydrothermal systems are dynamic (Figure 9-12). As they cool, hydrothermal systems "collapse" downward and younger alteration can overprint and destroy older alteration. If there is a new surge of intrusive or hydrothermal activity, telescoping of alteration zones may occur or cycles may repeat. Multiple episodes of magmatism confuse the simple picture and older events may be completely masked by younger. In simple systems, early potassic and propylitic alteration are overprinted by phyllic and later argillic alterations.

Bartos (1989) discussed prograde and retrograde alteration as they might relate to an underlying blind porphyry system. He found that two factors provided key clues: copper tends to be the dominant metal in lode deposits above porphyry systems; and alteration sequences in the overlying rocks tend to be prograde, that is, show increasing sulphidation and hydrogen ion activity.

HYPOGENE MINERALIZATION AND METAL PATTERNS

Hypogene ore minerals generally occur on fractures, in veins and as disseminations. Quartz is an abundant gangue mineral but chlorite and sericite are also common. Typical calcalkaline hypogene sulphides are pyrite, bornite, chalcopyrite and molybdenite; hypogene chalcocite occurs locally. Alkaline deposits generally lack economically important concentrations of molybdenite; many have associated pyrrhotite as well as pyrite. Metal zoning characterizes porphyry deposits. Generally, the central, hypogene copper-enriched zones are enclosed in pyritic envelopes; thus induced polarization has been a successful exploration tool for these deposits. Frequently, in calcalkaline settings (Figure 9-11a,b), a weakly mineralized or barren, often silicified core zone is rimmed by first a zone with bornite as the dominant sulphide (with molybdenite), then a zone in which chalcopyrite dominates (with molybdenite). In alkaline settings (Figure 9-13), core zones typically carry chalcopyrite, bornite, magnetite and pyrrhotite

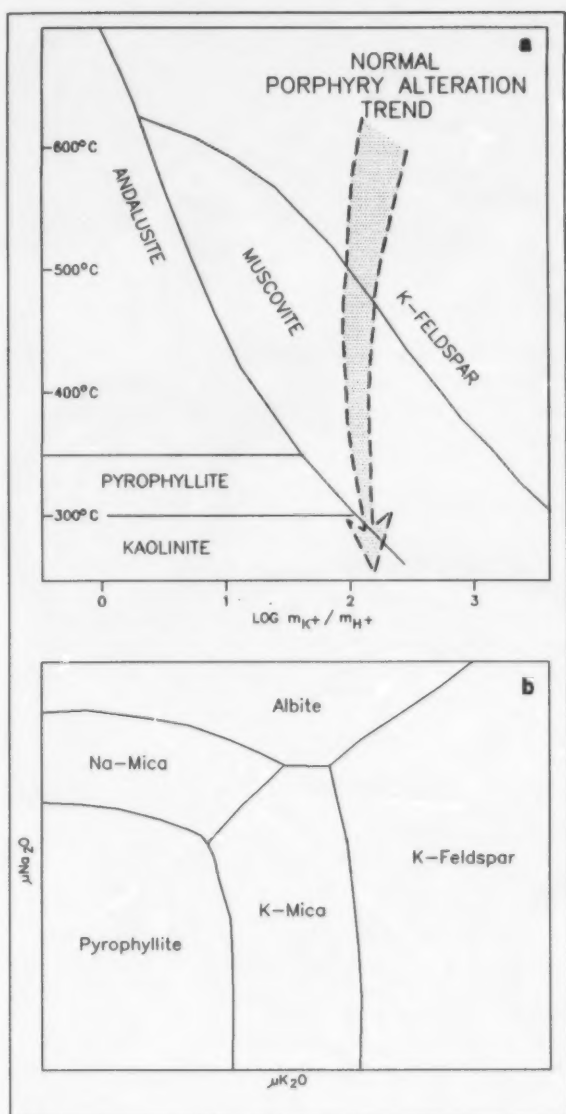
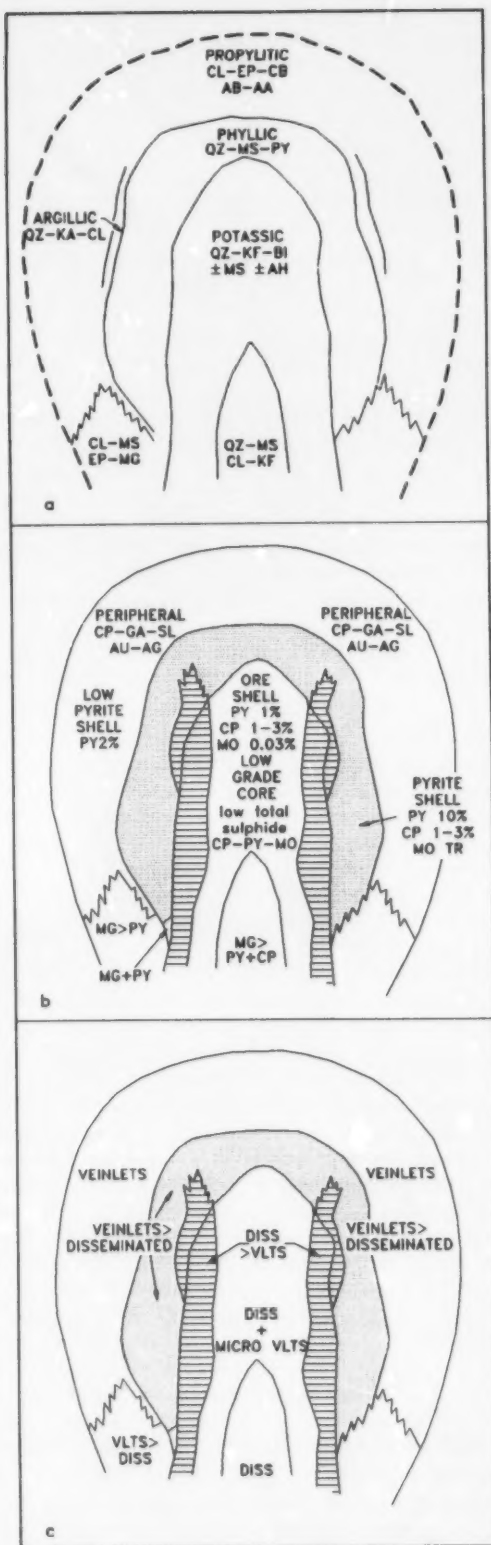


Figure 9-10a. Equilibria in the system $K_2O-Al_2O_3-SiO_2-H_2O$ with quartz present at 1 kilobar pressure (after Wodjak and Sinclair, 1984). 10b. Stability of phases in the system $K_2O-Na_2O-Al_2O_3-SiO_2-H_2O-HCl$ at 400°C and 1 kilobar pressure as a function of potassium and sodium activities; pyrophyllite is metastable (after Rose and Burt, 1979).

Figure 9-11. Schematic section through a typical southwest United States porphyry copper deposit (after Guilbert and Lowell, 1974). Abbreviations used are: QZ quartz, MS muscovite, CL chlorite, KF potassic feldspar, BI biotite, AH anhydrite, AB albite, AA adularia, CB carbonate, EP epidote, MG magnetite, AU gold, AG silver, CP chalcopyrite, PY pyrite, MO molybdenite, GA galena, SL sphalerite, VLTS veinlets, DISS disseminated.



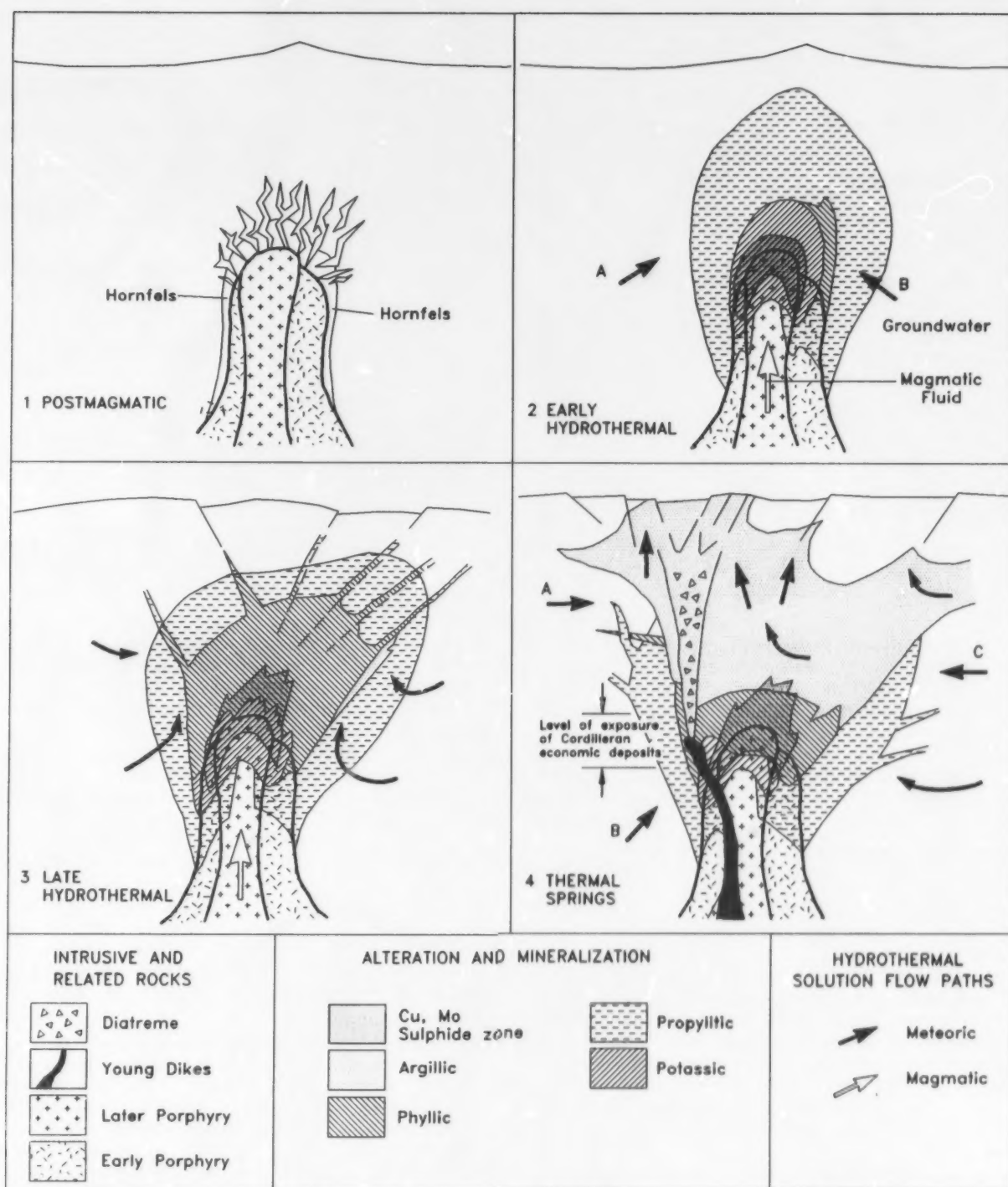


Figure 9-12. Model showing four sequential stages of alteration and mineralization that illustrate the possible evolution of a porphyry hydrothermal system (modified after Gustafson and Hunt, 1975).

with gold. In both settings the flanking pyritic shell gives way outward to a peripheral zone with base metal and perhaps precious metal skarns and veins. Precious metals in the hypogene assemblage tend to concentrate in the hot, central bornite zone, and in cooler peripheral zones. Mutschler and Mooney (in press) note that porphyry copper-silver-gold (PGE) deposits are related to shoshonitic magmatism, whereas gold-only porphyries are associated with felsic syenites.

Sillitoe and Bonham (1990) speculatively generalized available information to produce a schematic model to show the possible inter-relationship of sediment-hosted gold deposits and intrusion-centred base and precious metal deposits (Figure 9-14). Their model recognizes that ore deposits form during a continuum of related processes, so one deposit type often grades to another. Similarly, Jones *et al.* (1991) described a composite zoning model for a gold-enriched porphyry copper deposit. Central barren zones give way to zones characterized by: molybdenum; bornite-gold; chalcopyrite; pyrite with gold in shear zones; lead-zinc-silver; gold-silver veins; and finally, disseminated to replacement epithermal gold. They also noted multiple gold targets within these systems, particularly if they are hosted by carbonate-rich stratigraphic sequences.

CLASSIFICATION OF CORDILLERAN PORPHYRY DEPOSITS

CLASSIFICATION BASED ON MORPHOLOGY, ROCK ASSOCIATIONS AND DEPTH

Three end-member, morphological, depth-zoning models have been developed to describe porphyry deposits in the Canadian Cordillera (Sutherland Brown, 1976). They represent variations caused by tectonic setting and depth of pluton emplacement and, in British Columbia, are called **classic**, **volcanic** and **plutonic** deposit types. Their general characteristics are listed in Table 9-3.

Plutonic deposit types (Figure 9-15) form at relatively deep levels and are hosted by plutonic rocks; dikes and breccia bodies may be abundant. Alteration patterns are similar to those described for deposits in the southwest United States (Lowell and Guilbert, 1970; Guilbert and Lowell, 1974). They tend to be copper-molybdenum deposits with low gold values. Gold values are commonly less than 0.1 gram per tonne. Examples are the Highland Valley, Brenda and Gibraltar. At Lornex, in Highland Valley, for example, a central siliceous zone is flanked by potassic, propy-argillic-phyllic and propylitic alteration zones. The potassic zone is poorly defined because it is largely overprinted by propy-argillic assemblages. In contrast, the potassic zone at Valley Copper is well-defined by potassic feldspar in and adjacent to quartz veins and related to vein sericitic alteration (Osatenko and Jones, 1976). Metal zoning

at Lornex consists of a central zone with bornite and chalcopyrite, an intermediate chalcopyrite-dominated zone, a pyrite plus chalcopyrite zone and a pyrite-dominated fringing zone (Waldner *et al.*, 1976). That at Valley Copper is similar, except that the pyrite zone is poorly developed in the relatively leucocratic granodiorite to quartz monzonite host rock. In both deposits molybdenite is most abundant away from the bornite zone.

Volcanic deposit types (Figure 9-16) form in the root zones of ancient volcanos of both calcalkalic and alkalic character in association with subvolcanic stocks, plugs, sills and dike swarms. The country rocks, which host most of the ore, are largely volcanic rocks, breccias and dikes. Early developed biotite, which McMillan and Panteleyev (1988) argue may be hornfelsing, is typical, and propylitic alteration extends well out into the country rock from the deposits. Calcalkalic Cordilleran examples are Island Copper and Schaft Creek; alkalic examples are Galore Creek, Afton, Copper Mountain-Ingerbelle, and Mount Milligan. Examples are discussed in more detail in a later section. It is important to note that calcalkalic phases often occur within the suites of intrusive rocks that contain both alkalic members and alkalic porphyry deposits (V.F. Hollister, personal communication, 1991).

Classic deposit types (Figure 9-17) are related to multiple subvolcanic plutons. Host-rocks may be volcanic or sedimentary; dikes and breccias are common. Early developed biotite is characteristic and the change of biotite colour from green in the aureole to brown in the ore zone may provide a "vector" to guide exploration (Carson and Jambor, 1974). These deposits are close analogues of Tertiary porphyries in the southwest United States (Lowell and Guilbert, 1970; Guilbert and Lowell, 1974). Examples are Granisle, Morrison, Bell, Fish Lake and Poison Mountain. Late Cretaceous to Tertiary deposits in British Columbia are mainly of the classic type. At Granisle, for example, Fahni *et al.* (1976) associate the porphyry copper deposit with multiple porphyry intrusions of Eocene age that cut Jurassic volcanic and sedimentary country rocks. Copper mineralization is centred on the contact between biotite-feldspar porphyry and an earlier quartz diorite porphyry. The main zone consists of chalcopyrite and bornite in quartz-filled fractures and is enclosed in a pyritic halo. Alteration zoning is well-developed, from a potassic core, with secondary biotite, through a flanking phyllic zone, characterized by quartz-sericite-carbonate-pyrite assemblages, to a propylitic fringe with chlorite, carbonate and epidote alteration.

Gold-enhanced porphyry deposits fall within the volcanic and classic deposit types, whereas the gold-poor deposits fall in the plutonic deposit type. Gold values in the volcanic and classic deposits can be significant, in the 0.3 to 0.7 gram per tonne range (Table 9-2).

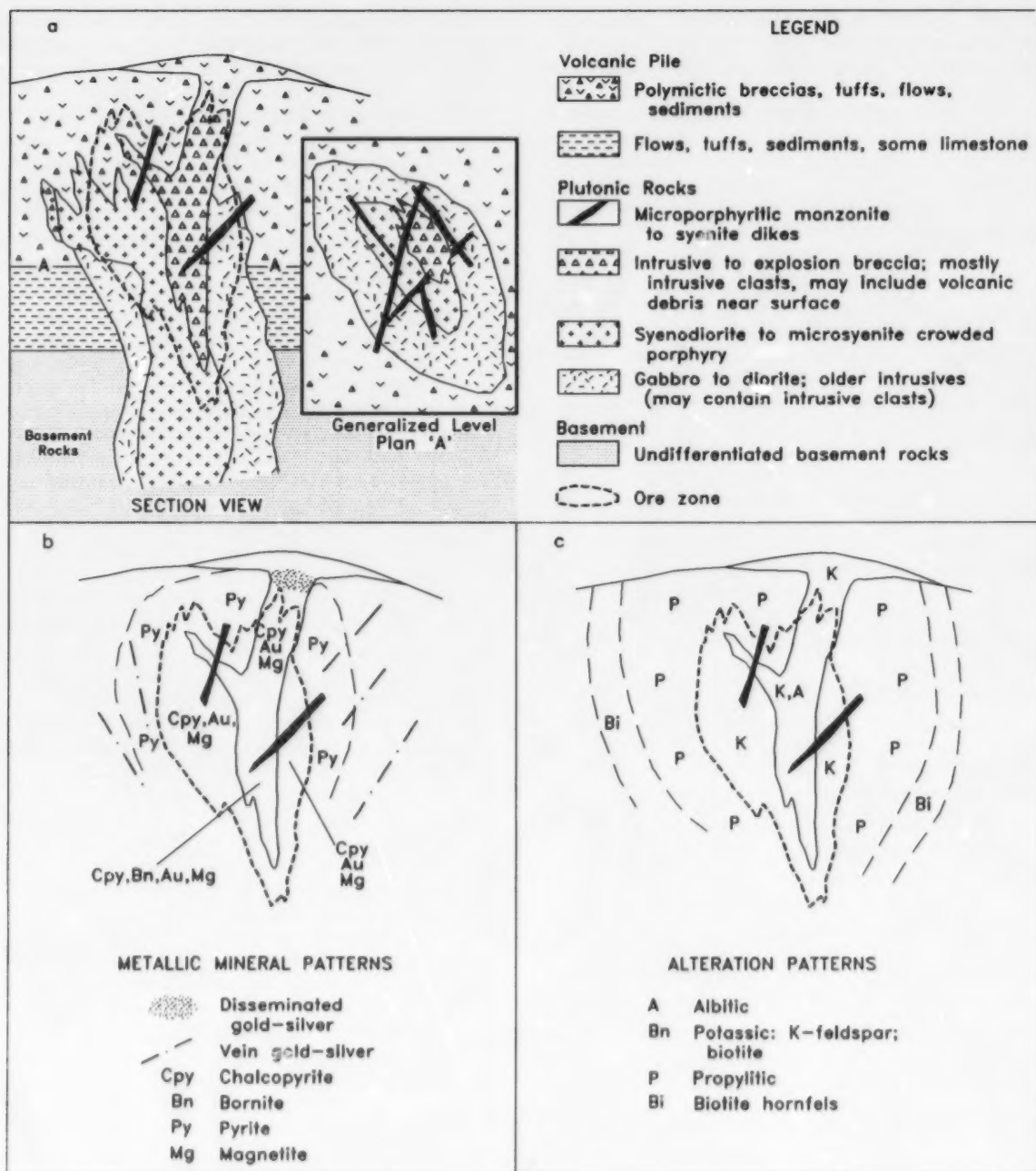


Figure 9-13. Model of typical alkalic porphyry copper-gold deposit (draws heavily on data from Fox, 1989; Preto, 1989; Mutschler and Mooney, in press; and others).

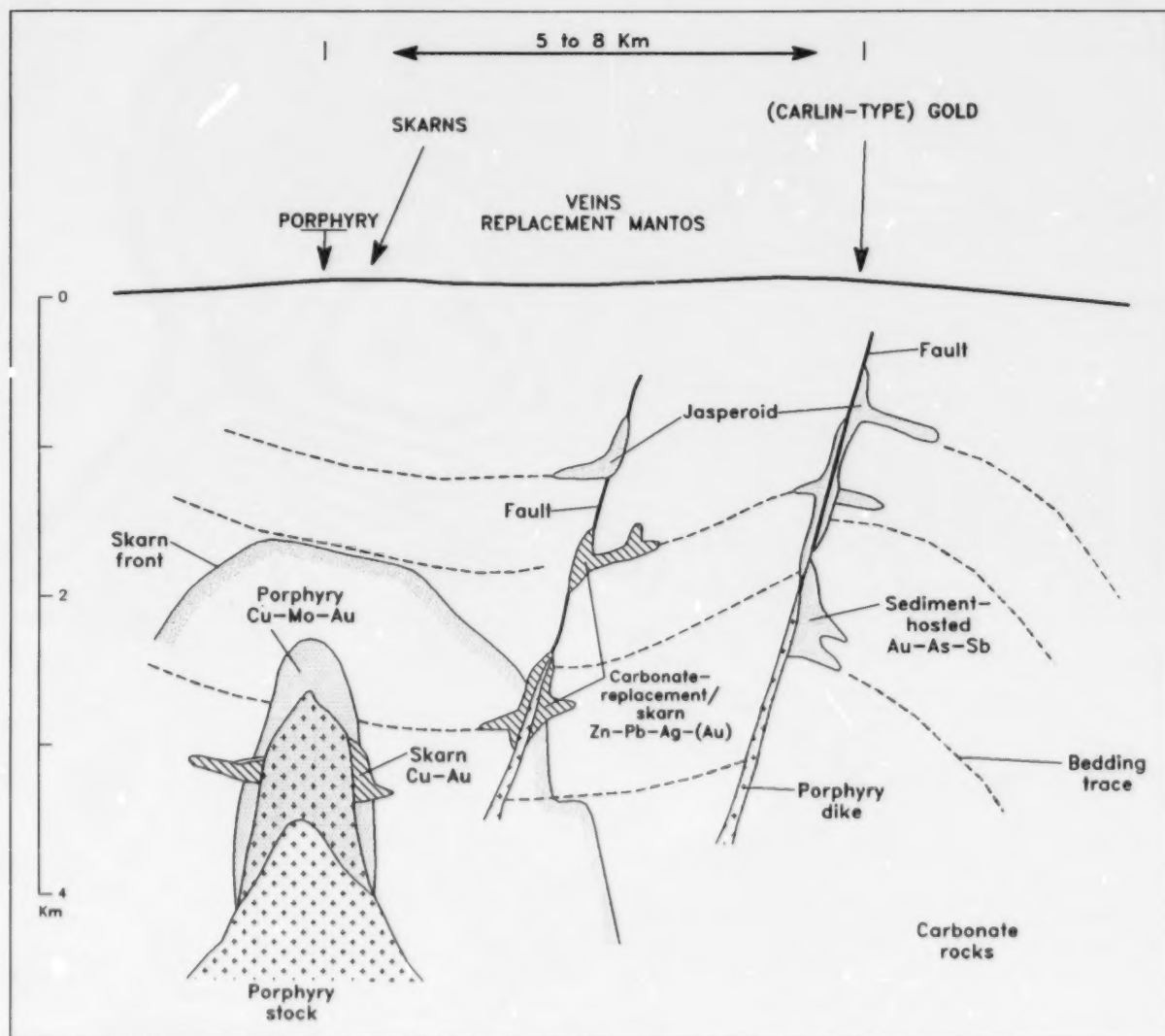


Figure 9-14. Schematic model of possible links between porphyry districts and sediment-hosted gold deposits (after Sillitoe and Bonham, 1990).

CHEMICAL CLASSIFICATION: CALCALKALIC AND ALKALIC CLASSES

In British Columbia, a second major distinction in classification is made between porphyry deposits related to calcalkalic versus those related to alkalic intrusive rocks. Calcalkalic deposits include plutonic, volcanic and classic types. Alkalic deposits (Barr *et al.*, 1976; Fox, 1989) are dominantly volcanic type, although some might be variations on the classic type. The distinction is important because, although they tend to be smaller, copper and gold grades are generally higher for known deposits in the alkalic class of porphyries (Figure 9-6). According

to Fox (1989) common characteristics of many alkalic porphyry deposits are: association with high-level stocks and dike complexes, for example at Mount Milligan, Mount Polley (Cariboo Bell), Ingerbelle, Galore Creek and Afton; association with zoned stocks, such as at Shiko, Kwun and QR (all in the Quesnel trough); or association with cumulates, such as at Mount Polley, Cantin Creek and perhaps the Tulameen ultramafic complex, north of Copper Mountain. The dikes are generally felsic and may be coeval to accumulations of felsic breccia; some of the breccias are intrusive, although they may carry extrusive clasts, such as Preto (1973) described at Afton. Extrusive breccias may also contain coeval

TABLE 9-3

Characteristics of Typical Cordilleran Porphyry Copper Deposits for Each of the Three Major Deposit Types

	Classic (Stock-related)	Volcanic	Plutonic
Setting	Associated with post-orogenic stocks intruding unrelated host rocks; co-magmatic volcanic piles rarely preserved. Cordilleran deposits are of Late Mesozoic to Tertiary age.	In basic to intermediate volcanic piles intruded by comagmatic calcalkalic or alkalic (dioritic or shoshonitic suite) plutons; magmatism produces consanguineous and intimately associated intrusive/extrusive assemblages. Cordilleran deposits are of Mesozoic age.	In large calcalkalic plutons emplaced in or near comagmatic volcanic rocks; plutons typically have mafic borders and are moderately to strongly differentiated. Cordilleran deposits are of Mesozoic age.
Plutons	Multiple phases emplaced as successive, small (0.5 to 2 km ²), cylindrical porphyritic intrusions; numerous pre, intra, and post-mineral porphyry dikes; emplaced at shallow depth.	Calcalkalic — very small to small sheets, dikes and plugs (0.2 to 10 km ²), with much textural variation; subvolcanic emplacement. Alkalic — high level sheets, dikes and plugs associated with underlying differentiated mesozonal pluton or small batholith.	Batholithic rocks (>100 km ²) immobilized at relatively deep levels (2 to 4 km). Phaneritic coarse grained to porphyritic rocks with local swarms of pre to post-ore porphyritic dikes.
Structural Control of Intrusions	Passive, structure need not be significant; many stocks localized by intersections of regional faults.	Calcalkalic — emplacement in volcanic vents, fault zones, radial fractures. Alkalic — intrusive centres localized by regional structures. High level intrusive rocks invade volcanic vents and fault zones.	Diapiric emplacement; magmatic pulses and differentiation cause sharp to gradational internal phase boundaries.
Breccias	Abundant and characteristic; post-ore argillic diatremes are common. Other types present include collapse breccias, intrusive breccias, and carapace or stoping breccias. Early breccias can be mineralized.	Calcalkalic — common and diverse; include primary pyroclastic tephra, alteration pseudobreccias, vent agglomerate, shatter and igneous breccias. Mineralized breccias are characteristic; some contain magnetite or tourmaline. Alkalic — intrusive and volcanic breccias common and generally mineralized, as in calcalkalic types.	Common in association with late-stage porphyry dike swarms. Breccias pre, intra, and late-stage.
Alteration	Potassic, phyllic and propylitic universally developed as annular shells around intrusions; argillic of varying importance. Early developed biotite (EDB) can be part of an isochemical hornfels and has often been misidentified as part of the potassic zone.	Calcalkalic — propylitic is widespread; potassic is more restricted but can be intense; alteration centred on zones of high permeability. Similar to classic type deposits with small core zones of potassic and local phyllic and/or argillic shells. Alkalic — local intense to pneumatolytic potassic alteration; early hydrothermal biotite overprinted by propylitic, then by sodic and/or potassic (albite-K-feldspar) and rarely scapolite alteration.	Phyllic, propy-argillic, and propylitic types are best developed; local potassic alteration. Fracture controlled to pervasive, commonly as alteration envelopes on multistage fractures and veins. Centered on orebodies but patterns of zoning complicated by overprinting.
Ore bodies	In margins and adjacent to porphyry intrusion(s) as annular ore shells, or as domal cappings; pronounced lateral zoning. Pyrite is found throughout; the weakly mineralized core is surrounded by zones dominated by molybdenite, then chalcopyrite, and finally, a pyrite halo.	Calcalkalic — generally Cu-Mo deposits intimately associated with breccias and intensely altered rocks; orebodies lensoid and irregular, with some preferential bedding control. Most ores contain chalcopyrite with rare bornite or molybdenite as "dry" fracture fillings. Alkalic — generally Cu-Au deposits in intrusive breccias or in highly fractured country rock; some replace porous country rock. Locally magnetite-apatite of magmatic origin present as vein or breccia infillings; zoning is from chalcopyrite, with or without magnetite, and bornite outward to a pyrite halo.	Large and diffuse vein stockworks; some breccia control, some faults mineralized; sulphides relatively sparse. Zoning is evident with iron content increasing outward from bornite, to chalcopyrite, to pyrite-rich zones; Mo distribution is variable. Some deposits have low-grade quartz-rich core zones.

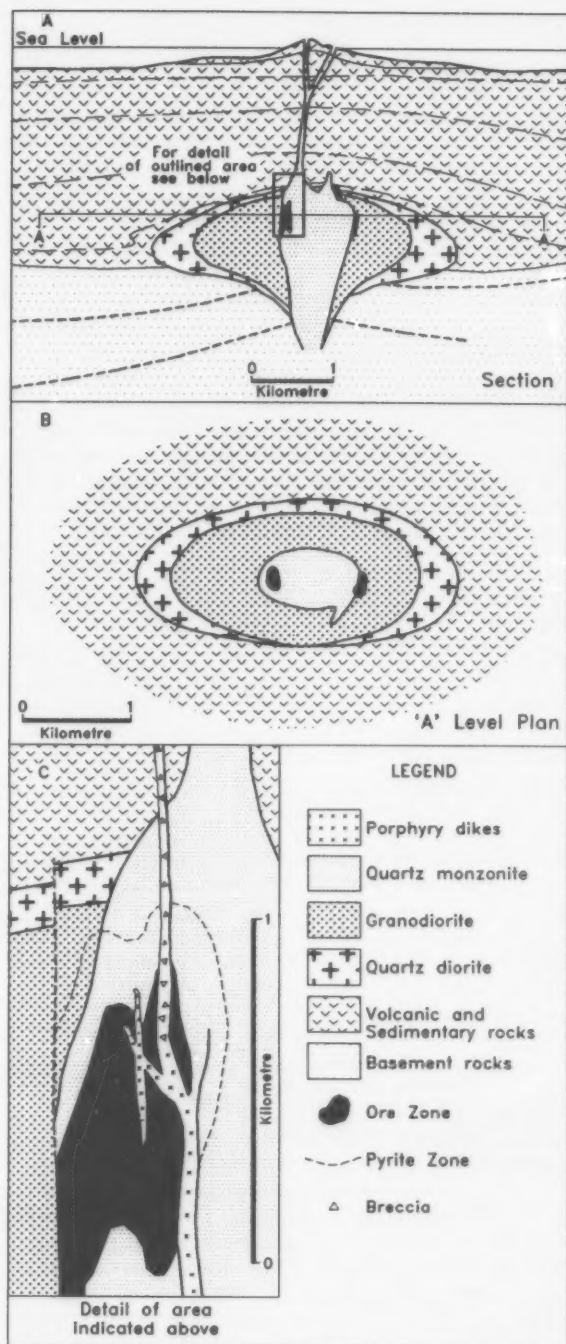


Figure 9-15. Model of Cordilleran plutonic-type porphyry copper deposits (after Sutherland Brown, 1976).

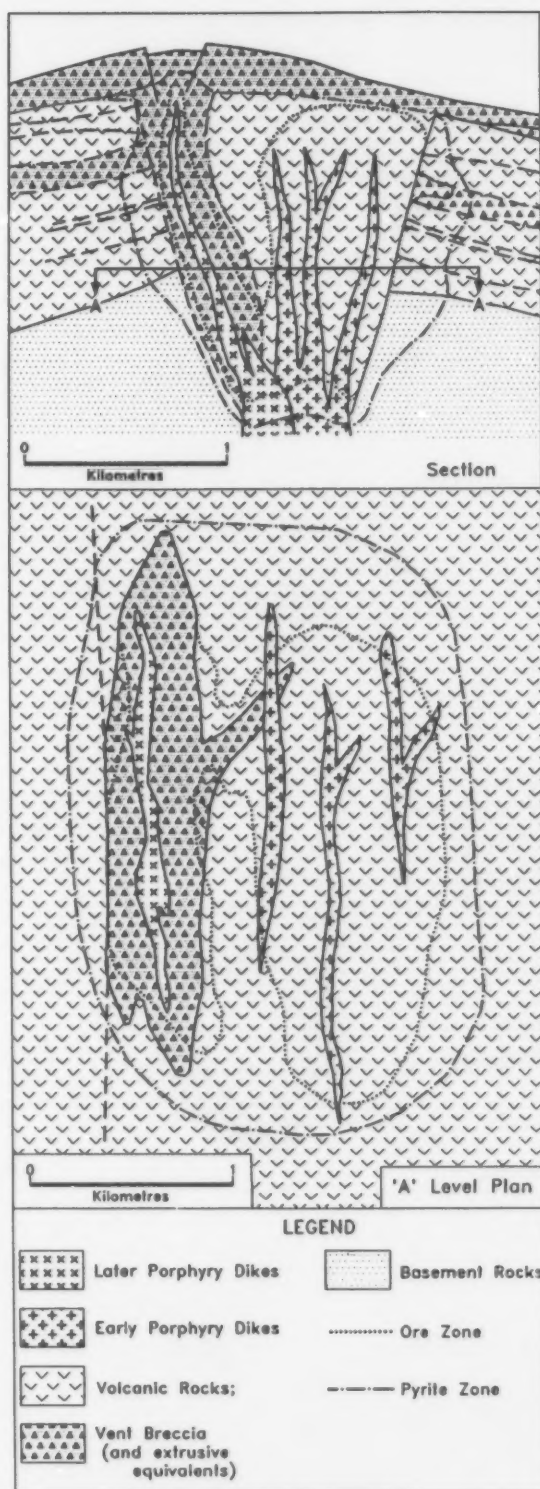


Figure 9-16. Model of Cordilleran volcanic-type porphyry copper deposits (after Sutherland Brown, 1976).

intrusive clasts. The stocks are zoned from cores of diorite through to syenite; differentiates may be sodic. Associated volcanic rocks may be shoshonitic; that is, alkalic rocks of basic to intermediate composition in which basalt members are nearly saturated in silica but have high total alkalis, alumina, ferric to ferrous iron ratios, carbon dioxide and fluorine. Generally, these rocks are also enriched in barium, rubidium, strontium, lead, light rare earths, thorium, uranium, copper and platinum group elements (Mutschler *et al.*, 1990).

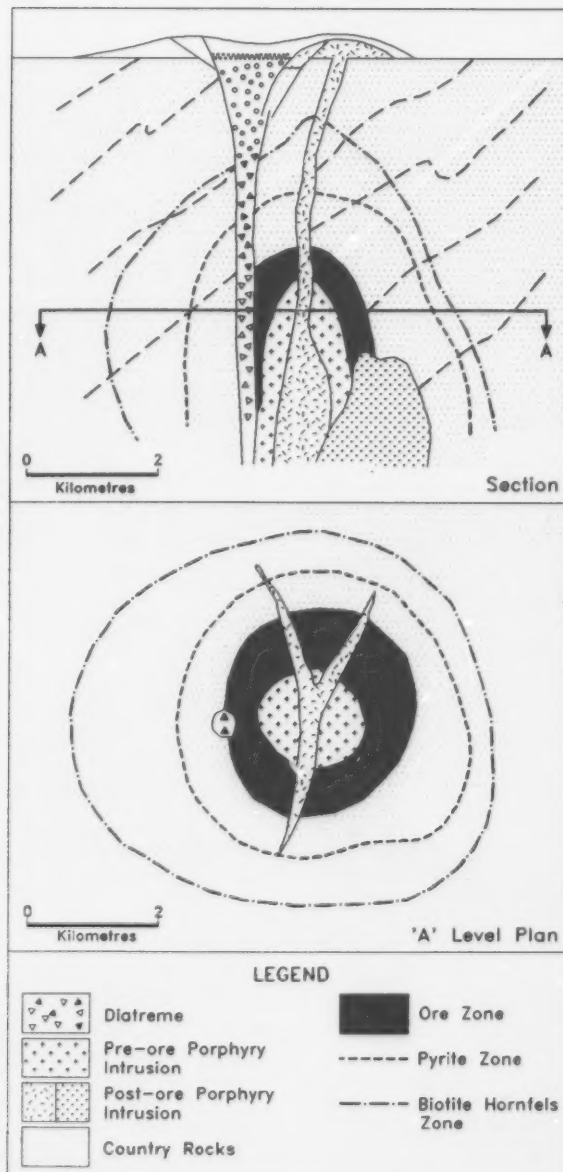


Figure 9-17. Model of Cordilleran classic-type porphyry copper deposits (after Sutherland Brown, 1976).

CLASSIFICATION BY METAL CONTENT

GOLD-RICH PORPHYRIES

As extraction technology advanced, low-grade gold deposits associated with intrusions became exploration targets. Geologists presently are defining characteristics for these deposits as was done twenty years ago for porphyry copper deposits. Sillitoe (1989b) arbitrarily defines a gold-rich porphyry as one with greater than 0.4 gram per tonne gold; gold values range to greater than 2 grams per tonne. These deposits possess all the characteristics of their gold-poor counterparts, albeit intensity of development of these features varies. Retrogressive alteration, usually to intermediate argillic sericite-clay-chlorite assemblages, partly overprints the early alteration, and phyllic alteration is poorly developed. The gold zones may be overprinted or flanked by intense argillic alteration developed both in the intrusions and the volcanic country rocks (Figure 9-18).

The related intrusions are I-type, magnetite series, hypabyssal and generally emplaced in the epizone. Typically the stocks are composite and 1 to 2 kilometres across with steep, cylindrical outlines (Figure 9-13). In well documented studies in the southwest Pacific and in South America, the stocks intrude coeval volcanic rocks in stratovolcano settings. Stocks range in composition from calcic, to low potassium through high potassium calcalkalic to potassic alkalic; few are in alkali-calcic rocks (Keith, 1983). In most related stocks $\text{FeO}/\text{Fe}_2\text{O}_3$ ratios exceed 0.5, and they are magnetite-rich. Leveille *et al.* (1988), who studied alkalinity-oxidation states, and Keith and Swan (1987), who compiled the $K_{57.5}$ index for many systems, concluded that relatively reduced oxidation states are characteristic of gold-enriched intrusions. Cox and Singer (1988) not only stress the importance of high magnetite content, but also the relatively high magnetite to pyrite ratio, which implies high oxygen relative to sulphur fugacity in the gold-enriched porphyries.

The majority of described gold-rich porphyries are Tertiary. In the Maricunga Belt, in northern Chile, for example, mineralization is related to a linear belt of Miocene volcanic rocks that are part of a series of composite calcalkaline stratovolcanoes (Vila and Sillitoe, 1991). The gold mineralization at the Marte deposit (Vila *et al.*, 1991) is coincident with a quartz veinlet stockwork and surrounded by intermediate argillic (chlorite-sericite-clay) alteration. The metallogenic cycle spanned 11 to 14 million years, which is important because it means that syn-mineralization erosion is considerable. This erosion can remove 1 or 2 kilometres of cover and cause superposition of shallower, younger alteration and mineralizing events on older, formerly deeper events. This theme is developed further by Sillitoe (1989a) in discussions about southwest Pacific intrusion-related deposits.

Gold in these systems is apparently introduced with potassic silicate alteration — biotite with or without potassic feldspar and/or actinolite (Sillitoe, 1989a). Sillitoe also found that gold and copper values are positively correlated or “connected”, thus many of these deposits can be viewed as “failed” pyritic porphyries with low copper and molybdenum values (Sillitoe, 1989b). Hydrothermal magnetite is commonly abundant in the potassium silicate zone. Gold:silver ratios tend to be low and gold generally occurs in native form. Gold most often forms as inclusions in or lies adjacent to pyrite, bornite and chalcopyrite grains. Sillitoe (1989b) notes that gold precipitates early, with any copper and molybdenum from chloride-rich fluids with temperatures from 400 to more than 600°C. Huyck (1990) found a similar zoning picture at Copper Mountain but concluded that gold in the propylitic zones was carried in bisulphide complexes and precipitated from lower temperature solutions. The hot ore fluids appear to have been dense hydrothermal brines that mixed with meteoric waters to create ascending plumes of mixed, lower density, sulphur and volatile-rich fluids. A complication is that these hydrothermal systems change with time. It is critical to study mineral paragenesis in order to understand the controls and distribution of the gold, because of its profound economic significance. In some instances, gold is partly decoupled from copper; at Mount Milligan, for example, gold concentrations increase with the pyrite:chalcopyrite ratio, not the copper concentration (Rebagliati and Copeland, 1989).

Metal zoning patterns around these deposits can be striking. Peripheral base metal deposits with precious metal values are both indicators to possible porphyries and potential economic targets themselves. Epithermal gold mineralization with quartz-alunite or pyrite-native sulphur-enargite acid sulphate type alteration may occur nearby. These typically form at 200 to 400°C from more dilute, later-forming, mixed source solutions than the potassium silicate zone gold. Most are located above the gold-rich porphyries. They present an attractive, underexplored potential target in British Columbia. Other commonly related showings are precious metal-bearing arsenic-bismuth-tellurium-tungsten skarns (Ettlinger and Ray, 1989) and breccia-hosted gold deposits. Some deposits have a copper-arsenic-gold association. Mutschler and Mooney (in press), in a model modified after Cameron and Hattori (1987), argue that the porphyry deposits and the epithermal deposits might be generated by two fluids evolved from the same magma chamber. An oxidized, carbon dioxide-saturated alkaline magma may exsolve a carbon dioxide-rich, highly saline, metal-bearing aqueous fluid that unmixes into immiscible phases. One phase is highly saline with copper, iron, silver and PGEs partitioned into it as chlorine complexes; it can produce porphyry copper deposits. The second phase is a low salinity water-carbon dioxide fluid in which gold with or without arsenic, mercury, tung-

sten and antimony are concentrated as sulphur and/or tellurium complexes; it can produce gold-dominated epithermal deposits.

The source of the metals, and the gold in particular, remains controversial. The sulphur and chlorine-rich, magnetite-series granitic host intrusions are interpreted to be derived in part from dehydration and partial melting of subducted lithospheric slabs. A factor noted by Lowell (1989) is that gold-rich and gold-poor deposits in the same belt often have different ages, although he does not think that age is a controlling factor. Sillitoe (1987) stresses that gold-rich porphyries occur along discrete linear belts which he relates to the convergent plate margins. He concludes that relatively rapid, low angle subduction favors gold mineralization and the copper, molybdenum and gold are derived from asthenospheric mantle sources that are independent of crustal thickness or crustal contamination. Titley (1987), however, relates relative gold abundances and gold:silver ratios in Arizona deposits to the relative abundances of the metals in the underlying basement rocks. Obviously agreement has not been reached on this issue.

In British Columbia, Island Copper (Table 9-3) is a Volcanic-type calcalkalic porphyry copper, gold and molybdenum deposit in the accreted Wrangell Terrane of northern Vancouver Island. The deposit is arranged around a central dike-like rhyodacitic intrusion that cuts the host Jurassic Bonanza Group volcanics, which are dated at 180 million years. The

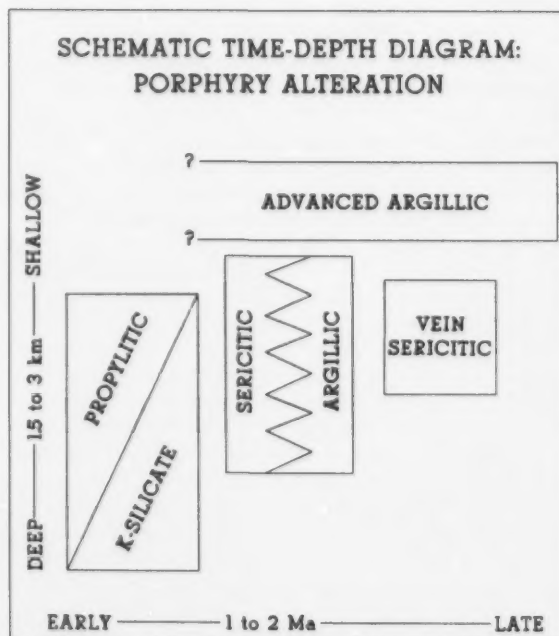


Figure 9-18. Depth and timing model for alteration related to gold-enriched porphyry copper deposits (modified after Sillitoe, 1991).

rhodacite is composite, with main, intramineral and late phases (Perello *et al.*, 1989). Although millhead gold values have averaged 0.22 gram per tonne, areas with 0.4 gram per tonne values are common. Copper and gold are positively correlated and approximately half the gold, which occurs as micron-sized inclusions in chalcopyrite, molybdenite and silicates, reports with the copper concentrates. Alteration and mineralization occurred in three stages. The earliest event produced a core zone of quartz, magnetite, amphibole and sodic feldspar which is partly overprinted by early potassic alteration characterized by hydrothermal biotite with magnetite, chalcopyrite, pyrite and molybdenite. Outward, in the propylitic zone, chloritic alteration gives way to epidote-dominated assemblages. Most of the gold was deposited in the potassic zone during this early phase. Intermediate stage alteration produced silicic and intermediate argillic assemblages (sericite-illite-smectite-chlorite), mainly in the porphyry. Quartz stockworks with sericite, chlorite and kaolinite alteration are associated with locally abundant pyrite, molybdenite and chalcopyrite mineralization. Gold may be related to this event but may have been remobilized. Marginal breccias and overlying intensely base-leached breccias with pyrophyllite, kaolinite, sericite and dumortierite dominate the late stage alteration. Ankerite-calcite veins, zeolites and local pyrobitumens also occur.

Fish Lake is a calcalkaline copper-gold porphyry of the Classic type (Table 9-3). The porphyry system occurs in an area of volcanic, sedimentary and porphyritic intrusive rocks within an embayment in the contact of a large, fine-grained porphyritic quartz diorite stock (Wolfhard, 1976). Contact metamorphism related to the various intrusions pervasively converted the country rock to biotite hornfels. A potassium-argon analysis of hornfels returned an apparent Late Cretaceous age of 77.2 ± 2.8 Ma. A wave of hydrothermal biotite alteration is superposed on the hornfels and in turn is overprinted by propy-argillic and propylitic alteration assemblages (McMillan, 1983). The deposit has pre-mineral mafic-plagioclase and quartz-plagioclase porphyry, and post-mineral mafic-plagioclase porphyry; early porphyries have biotite-altered groundmasses. Distinction between the porphyries and porphyritic extrusive rocks is based on alteration, recognition of clasts in the altered volcanics, or sharp contacts in the intrusives; in many instances, assignment is subjective, which is not surprising in this subvolcanic environment.

The best mineralization in the deposit is related to pervasive biotite alteration adjacent to and in "young" quartz-plagioclase porphyries (McMillan, 1983) and extends into flanking propy-argillic or intermediate argillic (Sillitoe, 1991) alteration that consists of sericite, quartz, carbonate and clays (Wolfhard, 1976). The propy-argillic zone partly laps onto the earlier potassic zone and is flanked by a propylitic zone. Earliest veins carry quartz, magne-

tite, hematite, sulphides and chlorite; during main stage mineralization, sulphides were deposited along with quartz, biotite, chlorite and sericite. Later veins are quartz, quartz with sulphides, carbonate, hematite and gypsum with chlorite or pyrite.

CORDILLERAN ALKALIC COPPER-GOLD PORPHYRIES

Fox (1989) described Cordilleran alkalic porphyry deposits as "schizophrenic cousins of real porphyry coppers". In compilations on a global scale, deposits of this class are relatively uncommon (Cox and Singer, 1988; Sillitoe, 1991) but they are vitally important in British Columbia. Subalkaline to alkaline, arguably shoshonitic, affiliations result from a conjunction of tectonic events. Yet these deposits occur along the length of the Canadian Cordillera, in two accreted tectonic terranes — Quesnellia and Stikinia, and during a very restricted period of time — late Triassic to Early Jurassic. The event was large scale and has not been repeated.

Solomon (1990) associated development of gold-rich magmas to arc reversals in island arcs in the southwest Pacific. They may also relate to deep-seated fracturing during late intra-arc extension or crustal slip faulting (Jones *et al.*, 1991). In Vancouver, in her talk for the CIM Annual General Meeting, April, 1991, Nelson likened the setting of ancient deposits in the Quesnel Belt to much younger events in Fiji and New Guinea in the southwest Pacific. There, when southeast-directed subduction was replaced by east-directed subduction rifts, transform faults and shoshonitic magmatism, characterized by high potassium, rubidium and strontium values, resulted. But it is not the intra-arc transform faults that are the gold exploration targets; the shoshonitic centers are distributed along linears that lie parallel to the transforms. Perhaps the epithermal gold deposits of Fiji and New Guinea herald underlying gold-enriched porphyries. Flanking or underlying the shoshonitic centres are areas characterized by calcalkalic magmatism. In British Columbia, similar magmatic relationships characterize the Nicola Group for example, where adjacent belts of alkaline and calcalkaline plutonic and volcanic rocks of similar age have fueled debate for decades (Preto, 1973; Preto *et al.*, 1979; Preto 1977; Mortimer, 1986). Nelson (1991) wondered whether the Pinchi fault in north-central British Columbia could be an analogous, fossil, Late Triassic transform fault related to alkaline and calcalkalic magmatism in the Quesnel Belt. We have much work to do to adequately test these ideas and their exploration implications.

Cordilleran alkalic porphyries relate to alkalic magmatic centres in the early Mesozoic island-arcs of Quesnellia and Stikinia. Host volcanic packages are predominantly pyroxene-bearing basaltic rocks of the Nicola, Takla and Stuhini Groups. These arcs began forming in Late Triassic (Carnian) time; magmatism ended in latest Triassic time in Quesnellia,

and in Early Jurassic (Sinemurian) time in Stikinia (Nelson, 1991).

Mutschler *et al.*, 1990 concluded that most alkaline magmas are partial mantle melts but that those with mineralization park, or halt their ascent, in the crust and fractionate to yield volatile and metal-enriched phases. According to Fox (1989) characteristic features of magmatic components of the alkalic magmatic centres are rapid emplacement, crystal fractionation, and local replacement of rest-magmas that are enriched in alkalis and depleted in iron. These result in multiple intrusions, porphyritic textures, microporphyries, intrusion breccias, intrusive breccias and magmatic, high copper-iron sulphides. Hydrothermal breccias are prominent at deposits such as Copper Mountain, Afton and Mount Milligan. Overlapping or telescoped alteration and mineralization events disrupt annular patterns and locally disseminated mineralization can exceed fracture-controlled ores. Phyllic alteration zones, and quartz veins and stockworks are uncommon in this setting.

Alkalic porphyry deposits relate to relatively evolved, often late phases of multiphase intrusions (Fox, 1989). The intrusions penetrate evolving volcanic edifices and breccia phases blast out to the surface where "boulder tracing" of felsic clasts in extrusive breccias can lead to intrusive centres and mineralization (Barr *et al.*, 1976). At Afton the main deposit is hosted in brecciated, late stage Cherry Creek micromonzonite and microsyenite. The 1.9 kilometre long Mount Milligan hydrothermal system (Rebagliati and Copeland, 1989; Harris, 1991) has annular shells of potassium silicate and propylitic alteration centred on the dike-like MBX and Silver Star porphyry stocks and related prominent breccias. The mineralized monzonites are distinctive crowded feldspar porphyries.

Both the main intrusions and the alkalic porphyries tend to lie along well defined tectonic features. The Iron Mask batholith "lies lengthwise in a major cross structure of the Quesnel Trough" (Carr and Reed, 1976). Preto (1989) and Nelson (1991) stress the importance of thinking of reactivated, older, porphyry-related structures when evaluating structures controlling Tertiary basins in the Intermontane Belt. Afton, Copper Mountain and Mount Milligan all have younger structurally controlled basins adjacent to them.

Alteration patterns are similar to those described for other gold-rich porphyries but differ in detail and are less consistently developed (Figure 9-13). Central potassic zones with potassic feldspar, biotite and magnetite contain much of the copper and gold mineralization. At Mount Milligan chalcopryrite and bornite with magnetite dominate (Delong *et al.*, 1991). Peripheral propylitic alteration zones, which Fox argues are early and temporally distinct from potassium-rich types, are characterized by epidote, chlorite, carbonate (ankerite) pyrite and minor chal-

copyrite. These zones may contain gold replacement lodes like the QR deposit. The model presented by Fox (1989) relates QR mineralization to intrusion of a zoned dioritic pluton into a pile of felsic breccias that overlie a calcareous siltstone unit. QR is not a porphyry in the strict sense, but a replacement deposit in the carbonate-rich unit within the metamorphic halo of the stock. Sillitoe (1989a) likened QR to a skarn and describes it and Equity Silver as being "arranged parallel to bedding as grossly manto-type bodies". Propylitic alteration zones also may carry small amounts of sphalerite, galena and uncommon arsenopyrite (Fox, 1989).

Where alkalic metasomatism is intense, albitization, rather than potassic feldspar, may occur. This sodic alteration produces albite, calcite, chlorite and epidote with associated pyrite and chalcopryrite (Fox, 1989). In the Iron Mask batholith, the series of alkalic porphyry deposits, including Afton and Ajax, have pervasive and vein-controlled albite. Albitization is also reported from Mount Milligan's 66 Zone.

In Stikinia, in northwestern British Columbia, the unusual Galore Creek alkalic porphyry deposit apparently formed in the throat of an ancient, 212 million year old (Logan and Panteleyev, 1991), volcano. Ten intrusive phases comprise the Galore Creek syenite complex and four have been related to porphyry-type mineralization. Ten copper deposits currently known are hosted in biotite, garnet and potassic feldspar-altered volcanic rocks and pipe-like breccia bodies (Allen *et al.*, 1976; Logan and Panteleyev, 1991). The orthoclase porphyries vary from fine grained to megacrystic and are pre, syn and post-mineralization. Mineralized volcanic rocks are genetically related shoshonitic basalts to alkali-enriched pyroclastic rocks that have been converted to skarns and coarse-grained fenitic porphyroids near mineralized zones (Allen *et al.*, 1976). Pervasive potassium metasomatism developed orthoclase, sericite and biotite in the volcanic country rocks and in the older syenite intrusions. Biotite also forms in veinlets up to 2.5 centimetres wide with anhydrite, chalcopryrite and/or bornite and occurs as breccia fillings with magnetite, anhydrite, garnet and chalcopryrite. Other alteration minerals include garnet, epidote, diopside, anhydrite and magnetite. Anhydrite replaces country rock minerals and forms veins to 1 metre in width. Mineralization consists of chalcopryrite, locally abundant bornite, lesser pyrite and rare hypogene chalcocite; pyrite and bornite are antithetic. Sphalerite and galena occur as sparse disseminations, particularly in garnet-rich zones. Copper and gold generally correlate positively, but while the gold is hosted in the copper-enriched zones, the highest gold grades are not necessarily coincident with the highest copper grades. Molybdenum content is negligible.

In a contrasting setting, Hollister (1991) describes structurally and lithologically-controlled auriferous quartz vein stockworks, such as the Fort Knox deposit in Alaska, as porphyry gold deposits; gold

mineralization is attributed to metamorphic remobilization from the country rock. There is no consensus whether these deposits should be included in the porphyry deposit classification scheme, but they do represent possible large, low grade, gold-rich targets.

SUPERGENE ALTERATION IN THE CORDILLERA

Supergene weathering and resulting alteration zones are not economically important at most Cordilleran porphyry deposits. Either glaciation removed supergene zones, or the zones that formed were thin due to cool climate, low sulphide contents or the presence of acid-destroying carbonate alteration. The few exceptions where significant supergene zones developed are Casino, in Yukon Territory, the Bell, Berg and Gibraltar deposits in central British Columbia, and Krain in the Highland Valley camp (Ney *et al.*, 1976). At Afton, oxidation destroyed sulphides and produced native copper, cuprite, chalcocite and other minerals, but did not augment the grade of the deposit. Thus the sulphide ore was oxidized but no enriched supergene blanket formed (Carr and Reed, 1976; Kwong, 1987). Immature, post-glacial, supergene blankets that have developed locally can cause metallurgical problems that diminish the grade of the copper concentrates. Pyrite can become encapsulated in thin covellite-chalcocite tarnishes and behave like copper minerals in the mill flotation cells (Panteleyev, personal communication, 1991). Recent discoveries with supergene mineralization and good assay grades are the Kerr property in the Iskut area of northwestern British Columbia, and the Kemess property, which is north of Mount Milligan, in north-central British Columbia.

HYDROTHERMAL SYSTEMS, TRANSPORT AND SOURCES OF METALS

Metal in porphyry systems is transported in concentrated sodium chloride brines. During the early alteration-mineralization stages in particular, these fluids contain a large component of magmatic water (Roedder, 1971; Sheppard *et al.*, 1971; Jones, 1975; Burnham, 1967; and many other studies). Later, especially as the hydrothermal system collapses, a significant amount of meteoric water is introduced (Gustafson and Hunt, 1975). Sulphur isotope data from El Salvador, Chile, agree; sulphur in sulphides is largely mantle-derived, that in sulphate minerals is mainly from meteoric sources. Similar sulphur isotope data were recorded at Cerro Verde, Peru (LeBel, 1979a,b). Arguments continue about the derivation of metals in porphyry deposits. Mutschler and Mooney (in press) propose a mantle source for metals in alkalic porphyries. Siilitoe (1989a) and Cline and Bodnar (1991) argue that much of the metal in

porphyry deposits is derived from the associated intrusions. It is relatively clear (McMillan, 1976) that copper in the plutonic Highland Valley deposits is derived from the rocks of the batholith, that is, the deposits are largely orthomagmatic (Figure 9-19). Another argument advanced is that the metals are derived mainly from the enclosing or underlying country rocks by convective hydrothermal fluids that are mainly of meteoric, metamorphic or mixed origin (Norton, 1978; Sheppard *et al.*, 1971). If this is true, then the intrusions act as heat engines to drive the convective cells.

EXPLORATION METHODS

One of the least expensive, most effective methods of exploring for porphyry deposits continues to be mapping and prospecting by well-trained exploration geologists and prospectors. On a regional scale, areas of interest could be identified by making tectonic reconstructions and studying initial strontium isotope ratios of intrusions. These data distinguish plutons with crustal contamination from those derived from the mantle or subducted oceanic

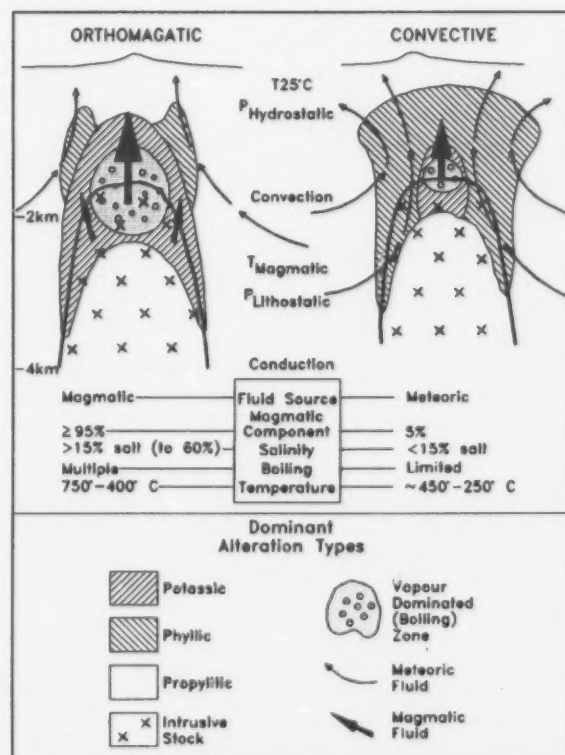


Figure 9-19. Model of hydrothermal systems with contrasting orthomagmatic and convective fluid flow patterns that could represent changes over the lifetime of the hydrothermal system (after McMillan and Panteleyev, 1988).

crust (Figure 9-9). Many porphyries are associated with mantle-derived intrusions in island-arc settings. Porphyry deposits tend to cluster in "districts"; many Geologists have stressed the importance of exploring near known deposits. Porphyry-generating hydrothermal systems are large; even buried deposits often have distinctive alteration zones in overlying rocks that can signal their presence (Bartos, 1989). Geophysical exploration methods that have been applied include: induced polarization, magnetic, gravity and radioactive element (for example potassium isotope) surveys. Fracture studies (Nielsen, 1976) at satellite, air photo and ground-truth scales can be useful. In British Columbia, especially in the Intermontane Belt, surficial geological studies to understand glacial movements and interpret surface-covering deposits — till, colluvium, glaciofluvial, glaciolacustrine — are vital if geochemical silt, soil and stream data are to be interpreted correctly (Gravel *et al.*, 1991; Bobrowski *et al.*, 1991). At the camp or property scale, useful guides are: silt, soil or rock geochemical studies; heavy mineral surveys; isotopic dating to pinpoint the "right" magmatic event; fluid inclusion analyses; lead, sulphur and oxygen isotopic studies; leach capping interpretation; and other tools from the mineral deposits research toolbox can be applied. Finally, detailed geological property mapping with trenching, computer modelling of whole-rock geochemistry, and extensive, widely spaced drill holes can be applied to outline a deposit and determine its economic potential.

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Vern A. Burkhardt
Queen's Printer for British Columbia©
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